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THE MEASUREMENT OF DIPOLE ANGLE DISTRIBUTION

FINAL TECHNICAL REPORT

BY

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INTRODUCTION

Background

Chaff has been in existence for more than forty years and it is perhaps remarkable that it has remained a viable countermeasure for so long, especially in the face of major advances in electronics and the resulting improvements in the capabilities of radars.

The fact that chaff remains viable today is demonstrated in its increasing use by all of the advanced countries, and by many of the less developed countries as well. It will be viable into the future, so far as it can be foreseen at the present time. One practical reason is the length of time required to introduce into service, and the service lifetime, of systems currently being developed. But a more important one is that its potential has yet to be fully exploited, or even understood.

Knowledge of even the basic characteristics of chaff is very limited and there is a great need to improve our understanding. This need was initially highlighted by the development of Warsaw Pact weapon systems and the extensive use of chaff by the countries of the Pact, but perhaps the most compelling reason is the recent growth in radar measurement capability in the West.

In the last few years realistic measurements of radar cross section of chaff clouds has become feasible, and indeed measurements over broad frequency bands and at different polarisations, all within the space of seconds, are now being made routinely and reliably. Radar measurement has produced a need for radar data analysis, of course, but a prequisite of analysis is knowledge of chaff characteristics. This knowledge has not been available.

Although there are several chaff materials currently available, market forces have dictated that only one, aluminised glass, will be used for the foreseeable future. This material has not been studied in any depth and yet it is known that dipoles made from it will perform specific motions as they fall through the air after being dispensed from an aircraft, rocket or other source.

The work reported here is intended to provide some understanding of those motions by examining the relationship between the angle at which dipoles fly and the number which fly at that angle in a chaff cloud, that is, the angular distribution of the dipoles.

At first sight the dipole angle distribution may appear to be only of academic interest. However, it can be shown that all dipoles are physically distorted and that there is a connection between the specific distortion of a dipole and its flight motion. In turn, the flight motion defines the dipole flight angle and the angle provides distinct characteristics to the radar response. An obvious example is the relationship between the horizontal and the vertical polarisation responses of the cloud. That is, the greater the angle of the dipoles to the horizontal plane the greater the vertical polarisation response at the expense of that in horizontal polarisation.

There is also an influence of dipole flight angle on the rate at which a chaff cloud grows in physical volume and, therefore, on radar cross section, but the

influence is more subtle. The overall growth of a cloud can be divided into two components for the purposes of analysis, growth in the horizontal plane and growth in the vertical plane. These two components can be translated into the horizontal travel of the dipoles and the differences in the fall velocities which cause the vertical growth of the cloud, since there is a range of dipole fall rates in any cloud, that is, dipoles do not all have the same fall velocity.

The growth rate of the cloud can be related to the dipole angle distribution since the greater the angle to the horizontal the more likely it is that the dipole will have a horizontal component to its velocity. This is a generalised statement since dipoles which fly absolutely vertically are obviously excluded, but in practical terms the statement is true even beyond 45 degrees. In addition, the greater the angle to the horizontal, the greater the fall velocity and, therefore, the greater the vertical growth rate. This view is somewhat oversimplified because the situation is complicated by other factors such as wind induced growth, turbulence, birdnests (that is, large quantities of tangled dipoles) and the effects of high dipole concentrations within the cloud. Indeed, one of the by-products of the work reported here has been an illustration of the effect of high dipole concentrations on growth rate.

Objectives

Since there is a distribution of flight angles amongst the dipoles in any particular chaff cloud it is essential to quantify the angle distribution to be able, in the longer term, to interpret radar measurement data of chaff clouds more accurately than before. The phrase 'in the longer term' has been used to indicate that the work reported here is intended as a first set of baseline measurements which have been made under the most simplified of simulated operational conditions and should not be taken as representing the full operational conditions.

The dipoles have been dropped into the equivalent of still air, effectively simulating the conditions experienced by a corridor of chaff. But the effects of aircraft turbulence, which would be of major importance in the self protect application, have not been simulated. The additional complications of turbulence etc. can be incorporated at a later date, after the baseline of still air conditions has been firmly established. It would be nonsensical to try to do everything at once when our knowledge of dipole aerodynamics is so small.

The objective of this study then was to measure the angle to the horizontal plane at which aluminised glass dipoles fly and also to count the number which fly at that angle in a cloud of single length dipoles. Since the angle distribution was expected to be time dependent to some unknown extent, the angle distribution was to be measured at intervals after the dipoles were deployed in the air to provide a measure of the time dependency. The whole experimental procedure was applied to four typical operational dipole lengths to assess how the characteristics changed with 'frequency'. The four dipole lengths were :-

10mm - 14.3 GHz - J Band
15mm - 9.5 GHz - I Band
28mm - 5.1 GHz - G Band
50mm - 2.9 GHz - E Band

The investigation has in fact significantly exceeded both the objectives and the requirements of the contract in that the experimental technique was so strong as to be able to demonstrate some of the mechanisms of dipole stablisation as well as some of the processes which cause clouds to grow. It is most unlikely that these achievements could have been made if another method had been used and it appears that the method could be developed further as will be discussed more fully under 'The development of the recording system' below.

Method

The direct measurement of the flight characteristics of dipoles and particularly of dipole angle can only be done photographically and there are of course substantial difficulties in being able to resolve dipoles well enough to measure their angles when the diameter is only 0.025mm (0.001in.) and the dipole length is 10mm. There is little point in resolving one or two dipoles; it is necessary to measure at least hundreds to enable the time dependence to be assessed. Hundreds of dipoles occupy a space which, although only about one metre in diameter during the period of interest, is vast compared with the dipole diameter. Correspondingly, the photographic techniques have to be a little unusual and a balance has to be struck between the maximum volume which can be used and the minumum standards of resolution which can be accepted. If dipoles are dropped into still air under laboratory conditions then they can be viewed for only about three seconds or so, using photographic means, because the fall rate is about 0.3 metres per second and the maximum distance of travel over which they can be recognised by the camera, adequately, is about one metre. That time scale is not really useful to study how the distribution changes with time. It is not feasible to have the camera track the centre of the cloud as it falls because of the very tight constraints on focus which are necessary to enable dipoles to be measured.

Measurement Techniques

The approach used in this work was to track the centre of the chaff cloud with a camera while giving the cloud a velocity equal to, but opposite in direction to, its mean fall velocity. This approach was based on the principle that if a dipole, which has a fall velocity in still air of 0.3 m/s, is dropped into an airstream which is travelling vertically upwards also at 0.3 m/s, then the actual fall rate of the dipole will be zero and the dipole will appear fixed in space and can be readily examined photographically. Similarly, if a cloud of dipoles is dropped into a smooth, controlled, vertical airstream where the air velocity has been carefully equalised across the width of the cloud then the growth of the cloud can be studied for tens of seconds and possibly even hundreds of seconds.

The apparatus used for this research is essentially a vertical, square section duct with a variable speed motor and fan combination installed at the bottom end. The fan draws air in from floor level and sends it vertically up the duct where it escapes at the top from the open end of the duct. The cross section of the duct is 1.15m (46in.) square and the height is 2.1m (7ft). Three of the walls of the working section, that is, that part of the duct where the chaff is dispersed and photographed, are made of glass and the fourth side is painted matt black for use as a photographic background. The height of the working section is 1.4m (55in). The details of the construction of the apparatus, which is traditionally referred to as a vertical wind tunnel, are described in the next section of this report.

The air velocity in the tunnel is very low, at only 0.3 m/s for aluminised glass, which is equivalent to about one third of normal walking pace. Indeed, it is so gentle that when reaching into the tunnel to retrieve a dipole, or to change its flight motion, it is not possible to feel the flow of air on the hand or face.

The airstream supporting the chaff cloud does not compress or affect it in any other way apart from removing the vertical component of the mean fall velocity. The full vertical and horizontal growth of the cloud are still visible and readily studied because the velocity differences are not affected. It is as if the camera was travelling down with the freely falling cloud.

The vertical wind tunnel method was first used to study chaff about 1970 and has been used continuously ever since. It is an established technique for the examination of clouds of dipoles under laboratory controlled conditions and it has already provided considerable information. Once the features of a chaff cloud have been recognised in the wind tunnel they are easily recognised in clouds deployed outside the tunnel in other laboratory experiments, whereas without the wind tunnel they are not recognised at all. When a cloud characteristic has been recognised and quantified it can be used in radar data interpretation and there has been some flow of information in that direction from previous wind tunnel studies. Characteristics such as flight motions, aerodynamic interaction of dipoles within the cloud and the growth of clouds have been studied . But the information gained has been more qualitative than quantitative and relates mainly to alumimium and metallised plastic dipoles rather than to aluminised glass ones which have not been studied to the extent that their predominance in volume usage would justify.

It has also become clear that there is a much more serious gap in our knowledge because it is now realised that many more of the characteristics of dipole clouds are very strongly time dependent and that there are very complex mechanisms causing that time dependence. This point has many implications in the interpretation of radar data from chaff clouds where absolutely everything is time dependent - radar cross section, polarisation ratios, frequency response, Doppler performance and resonance ratios, to name just a few, are strongly time dependent and no theoretical knowledge exists to explain how or why.

The work reported here is a significant step forward in the quantification of the dynamics of chaff clouds because it has analysed the time dependence of the dipole angle distribution. This has not been measured before.

It was necessary to develop further the wind tunnel and the recording techniques for this study to achieve its objectives. The wind tunnel was modified to obtain a more uniform air velocity profile across the chaff cloud and this is described in the next section. The photographic system, lighting system, analysis method and dipole dispensing method were also improved during the course of this work, and these are also described in later sections.

STRUCTURAL MODIFICATIONS TO THE WIND TUNNEL

Apart from the vertical wind tunnel used in this research, there are three others known to exist in the Western world, two in the UK and one in the USA. All four wind tunnels achieve a vertical airstream by using a variable speed motor to drive fan(s) and by passing the flow of air through a vertical glass-sided duct. This duct is usually about 0.9 metres square in the horizontal plane and the working section is about one metre high.

The essential requirement in these tunnels is to ensure that the air velocity is kept as constant as possible over the working area of the tunnel. This is to avoid any significant variations in air velocity as these will artificially change the dipole flight angle and cause a pronounced drift of the dipoles to one side of the tunnel. If the variations are particularly severe they will introduce a peculiar rotating turbulence which totally destroys normal dipole flight motions and makes the measurement of dipole angle meaningless.

The tunnels, other than the Cryptec one, attempt to overcome these problems either by gradually expanding the airflow path between the fan and the working section or by using a large number of small fans across the full working area of the tunnel. While these methods are adequate for demonstration purposes and for measurements which just need a chaff cloud, they are not suitable for detailed measurements of dipoles in flight.

The main reason why such approaches are unsuitable is that they make it difficult to achieve uniformity in air velocity. The gradual expansion method uses one fan, but its exhaust area is only about one tenth of the working section area. This makes it almost impossible to achieve a streamline flow when the path from the fan to the working section is limited to about one metre or so. Flow director plates have been inserted in to the air flow to ease this problem but these cause variations in the velocity profile across the chaff cloud when the motor speed is changed. It is very difficult to get a reasonable velocity profile using this method at the low air velocities which are used for aluminised glass measurements. The multiple fan method uses one controller for all of the fans, which each have their own integral motor. The method gives a very compact tunnel, but it has the disadvantage that variations in individual fan characteristics cannot be compensated for, again leading to variations in air velocity.

To overcome these limitations, the Cryptec tunnel used for this work incorporates several important structural modifications which have proved invaluable in this research. Firstly, the tunnel uses a single fan driven by a variable speed DC motor with a thyristor controller. This combination gives a fan speed range of 100:1. The motor and fan are incorporated into the base of the tunnel to give a very compact piece of equipment.

Secondly, no attempt has been made to use a streamline flowpath or to use flow director plates. On the contrary, a new diffuser baffle assembly is incorporated directly into the fan exhaust to force the airflow perpendicularly towards the sides of the working section of the tunnel. This ensures that the cross sectional area of the airflow is immediately increased from that of the small fan aperture to that of the large area of the working section. In addition, the diffusing baffle method is less affected by fan speed variations than if flow director plates are fitted, which, as mentioned earlier, dramatically change the velocity profile when the fan speed is varied.

Inevitably, turbulence increases around the fan exhaust using a diffusing baffle process, but this problem is overcome by two further diffuser stages which are incorporated downstream of the fan and diffusing baffle combination. These additional diffusers are designed to provide a resistance to the airflow so that a pressure differential is built up across the diffusers in the direction of the airflow. The increase in pressure on the fan side of the diffuser tends to reduce lateral pressure differences on the diffuser, that is, perpendicular to the airstream and so helps to reduce velocity variations within the working section.

The first diffuser stage is closest to the fan and so has the highest pressure differential across it, parallel to the airstream. It was necessary, therefore, to obtain the best balance between the minimum velocity variation across the dipole cloud and the maximum pressure differential which the motor and fan combination could supply over the range of velocities needed for the angle distribution measurements. This was achieved by evaluating various media within the diffuser until the best type was found.

The second diffuser stage consists of two accurately made mesh layers which are fitted across the full cross section of the tunnel adjacent to the working area itself. This stage is intended to obtain and maintain conditions as uniform as possible across the tunnel with the minimum pressure differential parallel to the airstream. This was achieved by closely controlling the aperture size of the meshes during manufacture so that the air permeability characteristics were kept as constant as possible.

As leaks of air are a major source of problems in vertical wind tunnels considerable care was taken throughout these modifications to minimise leaks around the various components.

As a result of these modifications it was possible to achieve a substantial degree of uniformity in air velocity profile across the tunnel. To illustrate this uniformity, it can be assumed that the typical fall rate of an aluminised glass cloud is 0.3 metres per second (this statement is a broad generalisation but it is not relevant to qualify it here). If the airflow is set to give the same speed in the centre of the tunnel then the maximum variation anywhere across the working area of the tunnel is 0.01 metres per second about that level. This is the smallest variation achieved in any of the vertical wind tunnels which are used for studies on chaff.

The air velocity measurements in this report were obtained by a hot wire anemometer built for use and calibrated in the range 0 - 2 metres per second. Measurements in this region are notoriously difficult and it is not intended to convey the impression that the air velocity measurements reported here are of outstanding accuracy. In this work only the variation in velocity across the dipole cloud was important and considerable care was taken throughout to achieve as small a variation as possible using a commercially available laboratory instrument.

THE DEVELOPMENT OF THE RECORDING SYSTEM

The requirements placed on the recording system by the objectives were quite severe. It was necessary to register hundreds of moving dipoles, each about the diameter of a human hair, on film sufficiently clearly for the flight angle to be measured during the film analysis. A sequence of experimental tests was made on each part of the system to develop the method so as to reach the best possible standard of definition. To achieve this the operating limits of the components of the system were rigorously examined.

The system was composed of six main parts which were; the camera, the film, lens, lights, screens and the background against which the dipoles were filmed.

Initial work with a 16mm camera made it evident that an improvement in resolution was necessary over what that format could offer, particularly for the examination of the shortest dipoles. A search was made for a suitable 35mm camera and an Arriflex 35 model II was obtained. All of the filming reported here was done with this camera which gave a significant improvement in resolution over the 16mm capabilities. Further improvement would be possible by going to 70mm film and this might be necessary for the measurement of shorter dipole lengths below 10mm, such as those used for millimetre wave applications. A 70mm format would also be necessary if the investigation is extended to aluminium dipoles at some future occasion. Since these rotate rapidly they can have much greater flight angles and they produce different cloud growth characteristics.

Calculations were made to choose a suitable lens which would meet two requirements; firstly, to give a depth of field covering the full dimension of the tunnel's cross section along the line of sight, and, secondly, to get a field of view perpendicular to the line of sight which would be about equal to the width of the tunnel. These requirements were met by a 50mm focal length lens and the final choice was a 50mm, f2 Schneider lens.

It was found necessary to use two different fields of view for the experiments which were conducted early on in the work. The first, with a visible height of 0.7 metres in the centre of the tunnel, was needed to give an adequate definition for the two shorter dipole lengths of 10 and 15mm (J and I Band respectively). The second, where the visible height was the full 1.4m height of the glass, was necessary to get a suitable distance for a cloud of dipoles to stabilise, that is, for transient dipole motions to terminate.

There was no need to use high speed film since more light could be put on to the subject than was necessary and the dipole motion within the frame was quite slow. But definition was all important and so a low speed, high definition film was used. Kodak Plus X 5231, black and white filmstock was employed throughout the work; it was rated at ASA 64 (tungsten). There was no advantage in using colour film because the subject was a cloud of 'white' dipoles against a black background.

Resolution tests were made to ensure that the camera, lens and film combination were capable of providing a suitable image of the dipoles to be used in the final experiments. The tests included exposures of a standard lens test chart at various positions in the tunnel and also involved placing a small cloud of the shortest and the longest dipoles at the front and then at the back of the tunnel and filming them. Focus was held in the centre of the tunnel during these tests and so the assessment of the results gave a good

indication of recognition capabilities of the system in the final measurements.

A number of changes were made in the lighting conditions and aperture to get the best definition and then experiments were made in varying the lighting power. Quartz-halogen lighting units were used and tests were with 1, 2 and 4KW total power ratings at a colour temperature of 3400 degrees Kelvin. Briefly, these were to investigate the effect of total lighting power and the positions of the lighting units on the recognition of dipoles. The final measurements of angle distribution were made with two 2KW lights, both positioned above the tunnel.

Exposure tests were made by varying the aperture of the lens using the best lighting conditions from the previous experiments. The base line was obtained by taking the exposure meter reading of a matt finish aluminium sheet inclined relative to the lights and the direction of view of the camera so that there was no direct reflection into the lens. Various levels of overexposure were also investigated, particularly for the recognition and measurement of very short dipoles orientated close to the line of sight. Finally, short sequences of film were shot with the longest and shortest dipoles in dynamic clouds to assess the results of the development of the overall recording system.

THE FINAL MEASUREMENTS

This section describes the conditions under which the final measurements were made, that is, the arrangement of the rest of the measuring system relative to the wind tunnel and the numerical data that appear on the films. The actions which were taken in the recording sequence are also described.

The camera was permanently mounted on a heavy very stable tripod throughout the measurements and this was installed on a 'spreader', a device to prevent the tripod feet moving. Reference marks denoting the positions of the spreader were made on the floor so that repositioning was exact.

The direction of view of the camera was in the horizontal plane and perpendicular to the plane glass front of the tunnel. It was carefully arranged that the camera and the centre of the dipole cloud, when it was formed, were in the same horizontal plane. The camera did not need an individual screen between it and the glass because the camera had been shielded from all light sources and there were no significant reflections within the field of view.

The electronic stopwatch was positioned just in front f the glass and within the field of view of the camera so that it appeared on the right hand side of the frame. In all of the film sequences, except the airjet injection (15mm dipole length) ones, the dipole length was written on the glass so that it appeared on the left hand side of the frame.

The distance between the camera and the centre of the tunnel was 4.3m (14ft) for the two longer dipole lengths but less, 2.3m (7.5ft) for the two shorter dipole lengths because their angles were more difficult to measure. In other words, the distance between the camera and the dipole cloud was adjusted to give the maximum field of view commensurate with adequate definition. Later in the research additional improvements were made in the definition attainable, but too late to increase the range in this series of tests.

The wind tunnel was made ready for the final measurements of the dipole angle distribution by a series of actions before each film sequence was shot. These were the cleaning of the diffuser free of all chaff, cleaning the glass walls of the tunnel, reassembling the tunnel to its operational condition and then checking the air velocity profile across the tunnel with the anemometer.

The lighting system was then checked and the position of the screens and their corresponding shadows confirmed by viewing through the camera viewfinder.

The exposure was checked by supporting a sheet of matt finish aluminium in the centre of the tunnel at 45 degrees to the line of sight and to the direction of illumination.

A check was made that the camera was loaded with enough film for the series of shots to be made and the camera function was confirmed with a brief test during which the frame rate was confirmed using the inbuilt meter on the camera.

The camera was finally checked for field of view and aperture settings and the point of focus was confirmed by suspending the lens test chart in the centre of the tunnel, with full illumination and the lens focussed on it. Neither the camera nor the lens were touched from that time onwards. It was not

necessary to touch the camera even in multi-shot sequences because it was electrically operated and remotely controlled.

The actual experiment started with the lights being brought up to full power from their standby, reduced power, mode and a three second countdown being given. At minus one second the camera was started, at zero the dipoles were injected into the tunnel and the timer started. The camera was kept running until five seconds and then switched off. It was switched on again at 9 seconds and off again at 11 seconds so as to catch the 10 second point in the middle of the shot. The 20, 40, 60 and where relevant, the 100 seconds events were recorded in a similar way.

After the film was processed it was projected as the negative, one frame at a time, on to white paper. The angle of each dipole was measured and its position marked on the paper so that it would not be recorded a second time. The angles were recorded in a histogram table and later transcribed into a graphical form of number of dipoles plotted against angle.

The original intention was to measure the angles to the horizontal of those dipoles which were nearly in line with the camera's direction of view by scanning adjacent frames of the film, waiting for the dipoles to rotate sufficiently, and then measuring them. This approach was abandoned very quickly for several reasons: it required an unreasonable amount of labour, it was not practical when there were 1000 or more dipoles on the frame and, lastly, the results were showing that the achievement of such accuracy was not altering the basic result. Since the 20, 40, 60 second series of results were showing a compatible sequence and, in doing so, showing that extreme accuracy was not justified, the angle of near end on dipoles was visually estimated direct from the projected frame.

In an effort to research the 0 to 5 second region of the cloud lifetime in more detail, small modifications were made to the system. These were designed to improve contrast further by placing additional screens around the tunnel so as to reduce reflections and thereby increase the density of shadows. The resulting quality of the photographic images was excellent and indeed better than anything achieved before this series of measurements. It was posible to see, recognise and measure dipoles as soon as 2 seconds after they had been launched. This limit was caused not by photographic quality, because dipoles in the cloud could be seen at zero, but by apparent physical contact between dipoles in the cloud which invalidated angle measurement when it was present. Dipole shielding also prevented analysis at these high densities.

RESULTS

Introduction

This section concentrates on the results of the film analysis which was made to establish the distribution of the flight angles of the four dipole lengths.

Some still photographs were taken from the original cine film. These are included here for the following reasons: to put the measurements which follow into context, to show what the chaff clouds look like in the wind tunnel and to illustrate some of the features which influence the rest of the results, in particular the rather complex processes operating in the first few seconds of the life of the cloud.

The detailed results are given in four series of graphs, one series for each dipole length, which show that the predominant flight angle is very close to the horizontal for all four dipole lengths.

A comparison is made between two methods of chaff dispersal and their effect on the angle distribution. The two methods were an airjet and a remotely controlled dispenser which dropped the dipoles in a vertical orientation.

Three bar charts have been derived from the basic data to summarise the results and are presented to illustrate the proportion of dipoles which are close to the horizontal. They also demonstrate the rapidity with which aluminised glass dipoles stabilise within the cloud.

In order to examine further the processes by which the dipoles stabilise into their flight motions, all four dipole lengths were dispersed by the remote controlled dispenser into still air and filmed. Photographs are reproduced from the film and the results of measurements are given to quantify the stabilisation distances.

Turning from a micro to a macro viewpoint, this section then examines the growth of the clouds in the wind tunnel by plotting and analysing the change in the dipole count obtained from the angle distribution film as a function of time.

A detailed account of the processes occurring during the stabilisation of the dipoles is given in the course of this section.

Dipole Angle Distribution For 20mm Dipoles

The 20mm dipoles were dispersed into the wind tunnel in which the air velocity was set at 0.3 metres per second, and filmed intermittantly at 24 frames per second over a time interval ranging from 0 to 100 seconds or so. The same procedure was followed with the three other dipole lengths, as discussed in the preceding section of this report. As the rate of change of the angle distribution was much slower than the frame rate, it was not necessary to analyse every frame of the film. Instead, the film was analysed at 20 second intervals for the greater part of each film sequence, but where the rate of change was greatest, that is, just after dipole launch, the analysis was made at more frequent intervals of 2, 5 and 10 seconds.

The photographic stills in Figure 1 have been printed direct from the film negative to illustrate generally what happens in the wind tunnel. There are

several preliminary photographs which show the growth of the cloud before analysis commenced at 2 seconds. Most of the remaining photographs show the times at which the angle distribution was measured and so correspond with the detailed graphs given later. Detailed measurements were not possible before 2 seconds because, as shown in the first three photographs, some of the dipoles were in contact with each other and the density was so high that dipoles at the front of the cloud were obscuring, and shielding, those at the back.

The stills were taken from a film shot at the longer of the two camera ranges used and each shows the whole working section of the wind tunnel. All of the side of the tunnel furthest from the camera is visible as are the two glass sides and the front of the tunnel. The bottom of the working section was the uppermost diffuser mesh and is readily apparent. The line drawn across the middle of the glass to mark the horizontal, and the dipole length written on the left hand side of the line show up reasonably well. The timer with its seconds and tenths of second digits can just be read in the bottom right hand corner of the frame, but for ease of reference each photograph also has its time identifier repeated underneath it.

The dipoles were dropped vertically into the tunnel for a period of about 1 second and some can be seen to be almost vertical at the top of the cloud in the first three photographs. However, most of the dipoles quickly rotated to the horizontal. Indeed, some of them had already reached there by 0.2 seconds. Generally, the horizotal dipoles were on the outside of the cloud and those at high angles were in a central strip immediately under the dispenser. But as soon as dispensing had stopped the high angle dipoles were no longer seen at the top of the cloud. Instead, they were constrained within a very high density region in the centre of the cloud.

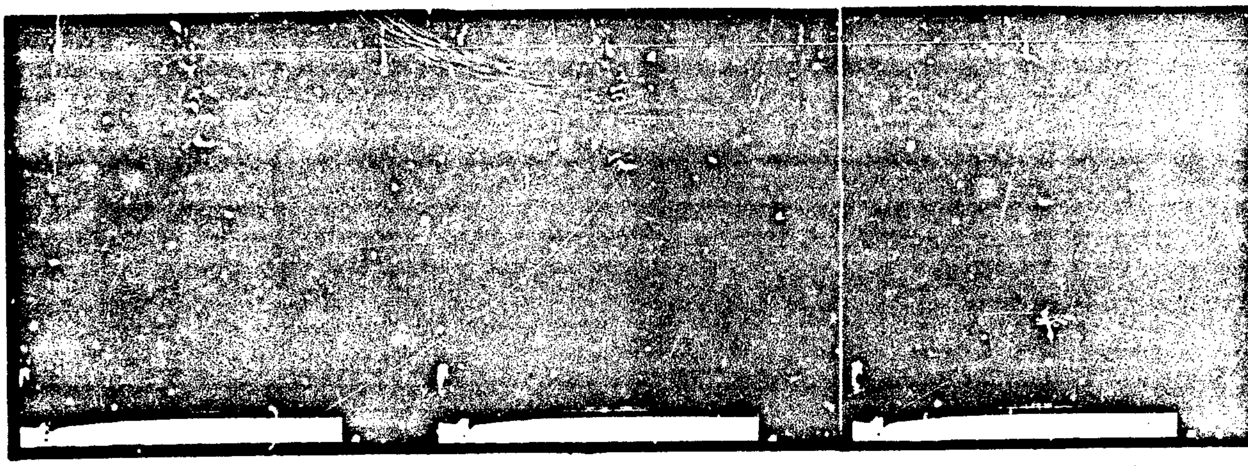
The central concentration of high angle dipoles which constitutes the interaction region will be frequently referred to in the rest of this report. It can be seen clearly in the 5 second photograph. But this high angle flight motion was transient since by 10 seconds and to some extent at 20 seconds the interaction has been transformed into vertical columns of horizontal dipoles.

Those dipoles which had a permanent high angle flight motion are evident at the bottom of the cloud in the 3 to 5 second period after dispensing. However, the number of dipoles involved was obviously a very small percentage of the total number of dipoles in the tunnel and these dipoles had virtually disappeared by 10 seconds, by then having impacted into the bottom mesh and staying there for the rest of the measurement period.

As the cloud grows and the distance between adjacent dipoles increases, sooner or later the physical limits of the dipole cloud exceed the dimensions of the tunnel. This occurred in the sequence of photographs after about 10 seconds, and from then on significant numbers of dipoles either hit the sides of the tunnel or the bottom mesh or were carried out of the open top of the tunnel. The decay in the number of dipoles visible in the field of view is the primary feature from 10 seconds onwards and is investigated further below. The only other point to note here is that the very small angle to the horizontal of all the dipoles continues to get even closer to the horizontal as time increases.

A small birdnest of tangled dipoles can be seen at the bottom of the cloud for the first four seconds of the lifetime of the cloud. It is not relevant to the angle distribution or the processes occurring within the cloud and should be disregarded. Incidentally, however, it does show how, in an operational

CLOUD GROWTH IN THE WIND TUNNEL
dipole length 28mm



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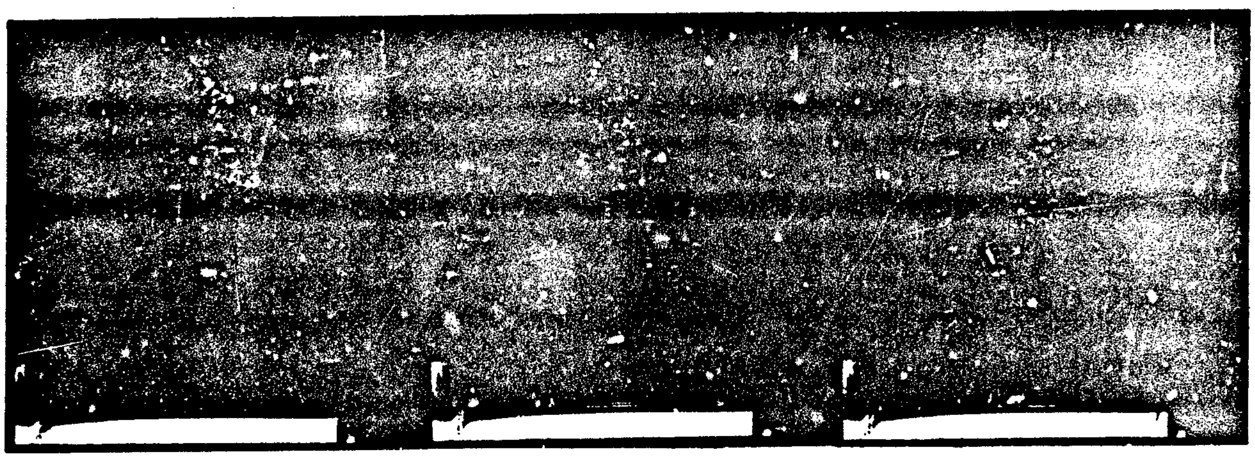
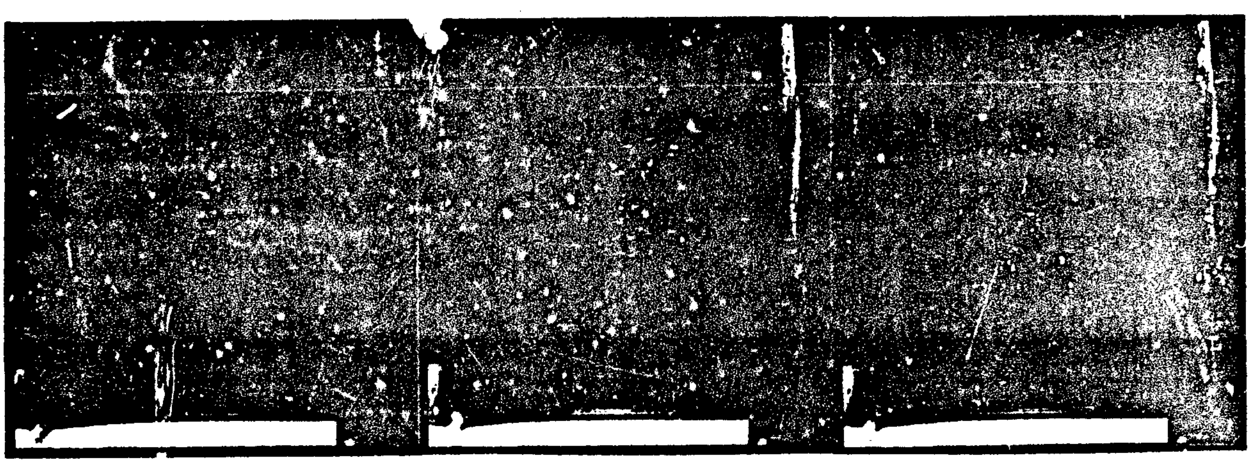


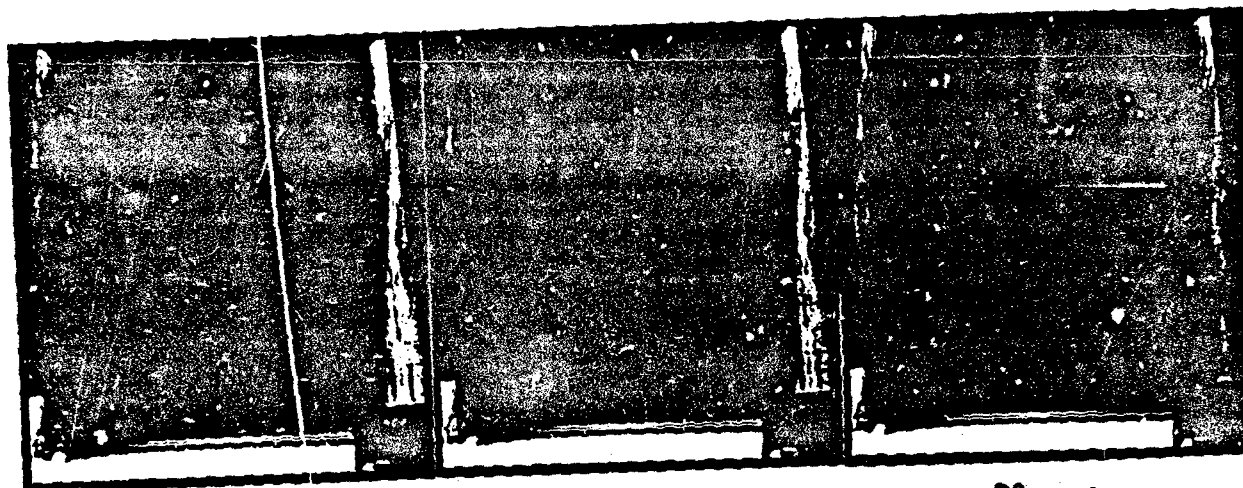
2·0 secs. 3·0 secs. 4·0 secs.



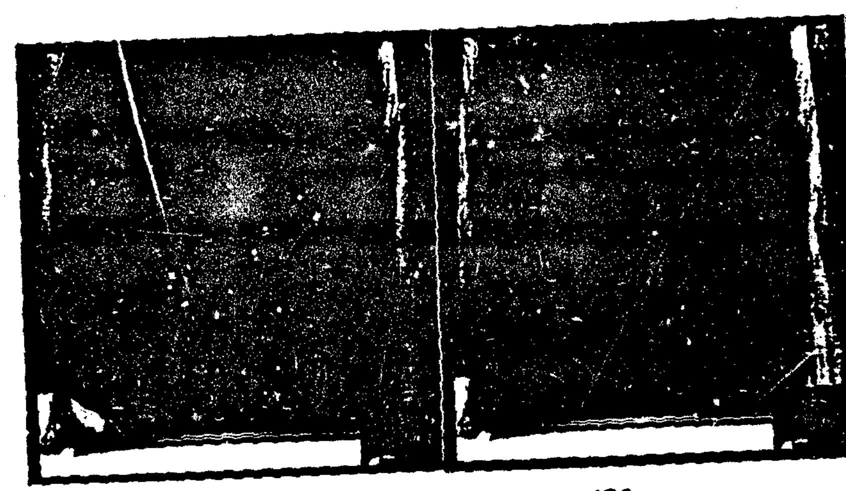
5·0 secs. 10 secs. 20 secs.

CLOUD GROWTH IN THE WIND TUNNEL

dipole length 28mm



40 secs. 60 secs. 80 secs.



100 secs. 150 secs.

cloud, the birdnests fall faster than the dipoles and drop out of the cloud first.

The dipole angle distributions for the 28mm dipoles are given in Figure 2. This figure graphs the number of dipoles recorded at each angle plotted against the dipole angle in one degree increments between 0 and 90 degrees to the horizontal. The graphs correspond to the sequence of photographs within the range of 2 to 100 seconds following the launch of dipoles into the wind tunnel. All the graphs have been plotted on the same scales to facilitate comparison between them and to reveal more clearly the pattern that unfolded.

The graph for 2 seconds after launch shows that the dipoles were reasonably evenly distributed over the full range from the horizontal to the vertical but that there was an apparent concentration between 0 and 10 degrees to the horizontal. This pattern confirms that shown in the still from the film.

However, the pattern at 5 seconds is very different from that at 2 seconds, as shown by the next graph in which the number of dipoles between 0 and 10 degrees has markedly increased, while those with a flight angle between 30 and 90 degrees have reduced.

The 10 second graph shows that the number of dipoles in the 0 to 5 degree region has grown further compared with the 5 second graph, whereas the number of dipoles with angles between 20 and 90 degrees has distinctly reduced.

The total number of dipoles recorded in each of these three graphs was 524 at 2 seconds; 541 at 5 seconds; and 496 at 10 seconds, that is, there was a variation of less than 10 per cent. It can be assumed, therefore, that the loss of dipoles from the field of view, by their hitting the side of the tunnel and so on was negligible

So, over the first ten seconds of the lifetime of the cloud, as recorded in the three graphs, there was an obvious trend of stabilisation of the dipole flight motions towards the horizontal and the process was quite rapid. The sequence of graphs, therefore, confirm and quantity the impression given by the photographs.

The dipole stabilisation process continues beyond 10 seconds, as indicated by the 20 second and subsequent photographs, but dipoles are progressively lost from the field of view after 10 seconds and this complicates interpretion.

Completely horizontal dipoles generally do not have a horizontal component to their velocity, but those which fly at angles up to 20 degrees do [compare with the 10 second graph], and they will hit the sides of the tunnel, become trapped in the boundary layer, fall to the bottom of the tunnel and be permanently lost. The photographs show that vertical dipoles, however small as a percentage, fall out of the cloud and they are also lost.

The number of dipoles at 20 seconds had reduced to 396, about a 20 per cent loss since the 10 second graph, and, therefore, care needs to be taken about ascribing any leftward drift in the peak of the distribution to dipole stabilisation, even though the photographs indicate that it was happening.

The rest of the distribution graphs at 40, 60 and 100 seconds illustrate the decay in dipole numbers clearly by themselves and do not need further comment.

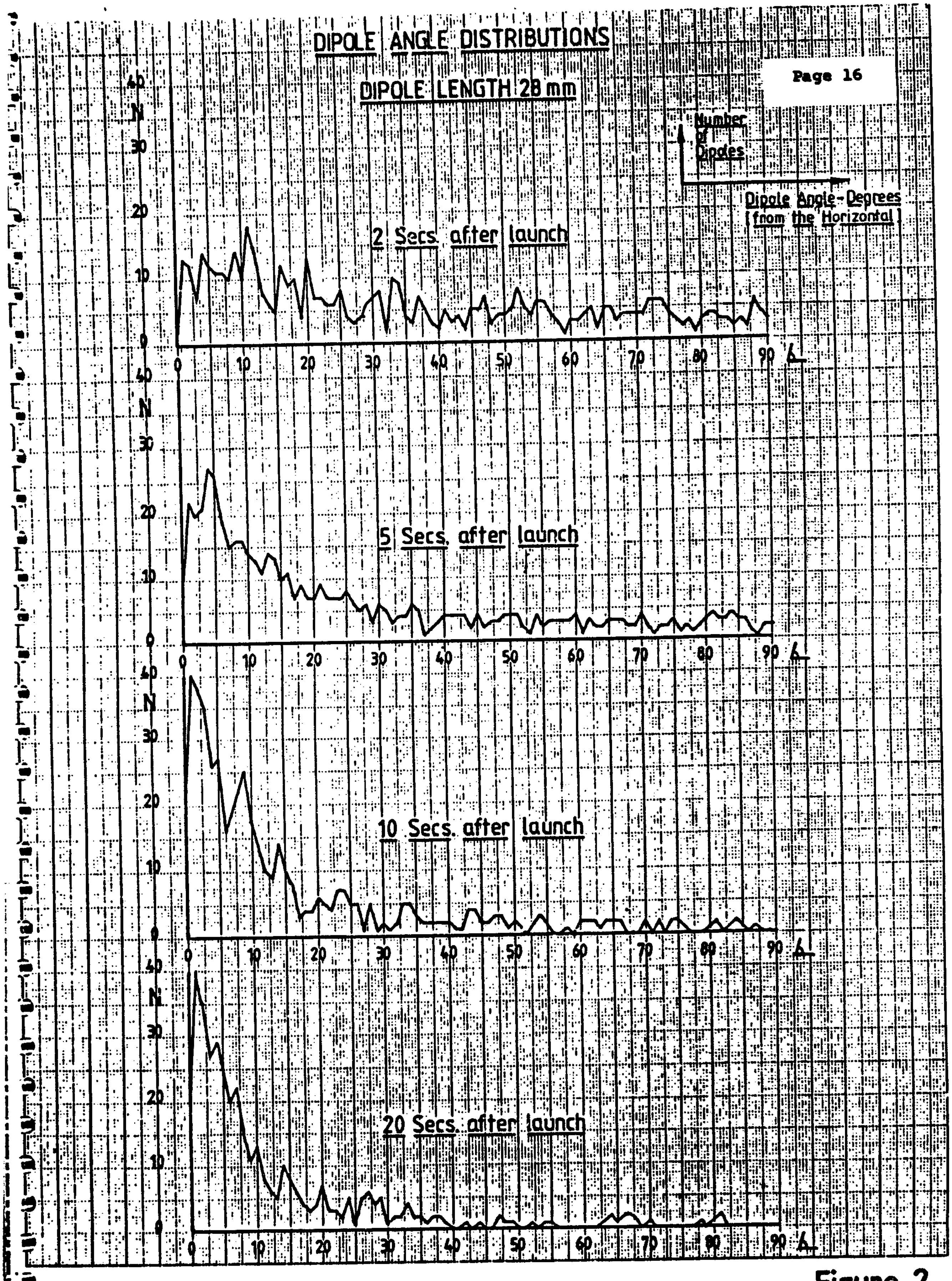

DIPOLE ANGLE DISTRIBUTIONS
DIPOLE LENGTH 28 mm
Number of Dipoles
Dipole Angle - Degrees (from the Horizontal)
2 Secs. after launch
5 Secs. after launch
10 Secs. after launch
20 Secs. after launch
N
0
10
20
30
40
50
60
70
80
90

Figure 2

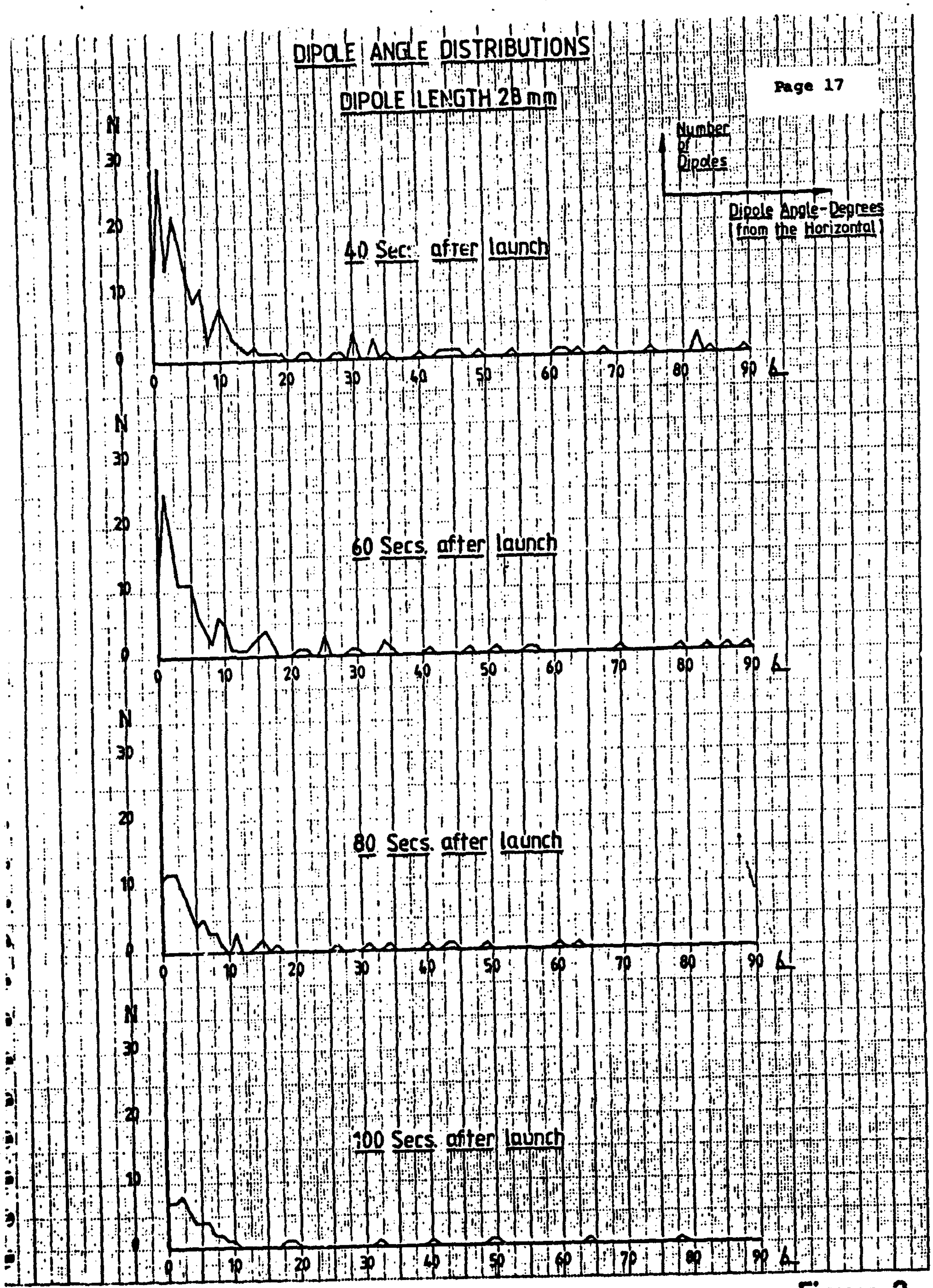

DIPOLE ANGLE DISTRIBUTIONS
DIPOLE LENGTH 28 mm
Number of Dipoles
Dipole Angle-Degrees (from the Horizontal)
40 Sec. after launch
60 Secs. after launch
80 Secs. after launch
100 Secs. after launch
N
30
20
10
0
0
10
20
30
40
50
60
70
80
90

Figure 2

Essentially, the wind tunnel method examines what is happening in a fixed volume of space. The dipole cloud grows rapidly in volume from the moment that it is formed, and for the first 10 seconds or so it occupies a physically smaller volume of space than the volume examined. Beyond about 10 seconds the cloud volume is greater than the field of view and the results after that time should be viewed with that point in mind. A radar which looks at a chaff cloud does the same thing of course, since the cloud is initially smaller than the resolution cell of the radar, but sooner or later the cloud grows beyond the radar.

While no method of examining dipole flight can be perfect, the fact that the shape of the angle distribution graph does not change significantly with time, even though the dipole number, or amplitude of the graph, changes markedly, indicates that the method possesses validity beyond 10 seconds.

No investigation has been made of the rate of dipole loss from the six individual faces of the field of view, but the overall dipole number versus time relationship has been examined further later in this section.

Dipole Angle Distribution For 10mm Dipoles.

A sequence of stills taken from the film of the 10mm cloud is given in Figure 3. The film was shot as the shorter of the two camera ranges because it was necessary to obtain a large enough image for the analysis of the very short dipoles. It is difficult to form an impression of the field of view because very little of the tunnel appears in the stills compared with the 28mm sequence of stills above. However, they can be related by noting that the horizontal line and the dipole length digits in the bottom left hand corner are in exactly the same position on the glass front of the tunnel. The width of the field of view, as presented in both sets of stills is about the same - for the 28mm sequence the width is exactly the width of the tunnel's back wall, which constituted the black background to the dipole cloud. The original negative of the 10mm film was also the background width, but the photographs have been slightly trimmed on the right hand side.

Although the 10mm dipoles were dispensed so that they were initially vertical this cannot be seen in the photographic stills in the way that it could in the 28mm sequence. The 10mm cloud came in to view in the earlier frames of the film looking the same as it does in the 2 second still with vertical dipoles only in the centre of the cloud.

The dipoles were so close together, as can be seen at 2 seconds, that angle measurement was not feasible then or, indeed below 5 seconds at all, even though the frame was magnified up to 0.5 metres for analysis.

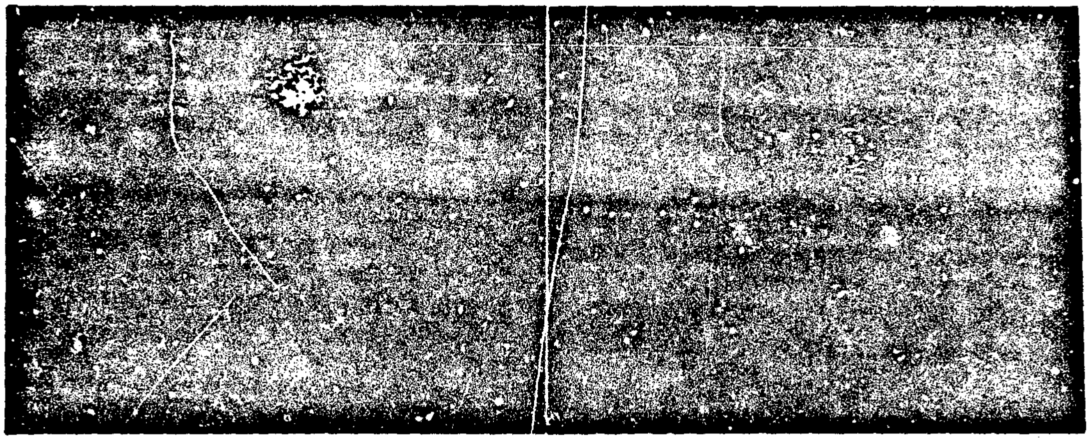
The 10mm cloud apparently occupies a much smaller volume than the 28mm one in the early stages of its life, according to the 2 and 5 second stills.

There is nothing in the films to indicate why this should be so, but the results of the zero velocity experiments which are reported later may provide some insight into why the two clouds should differ so much.

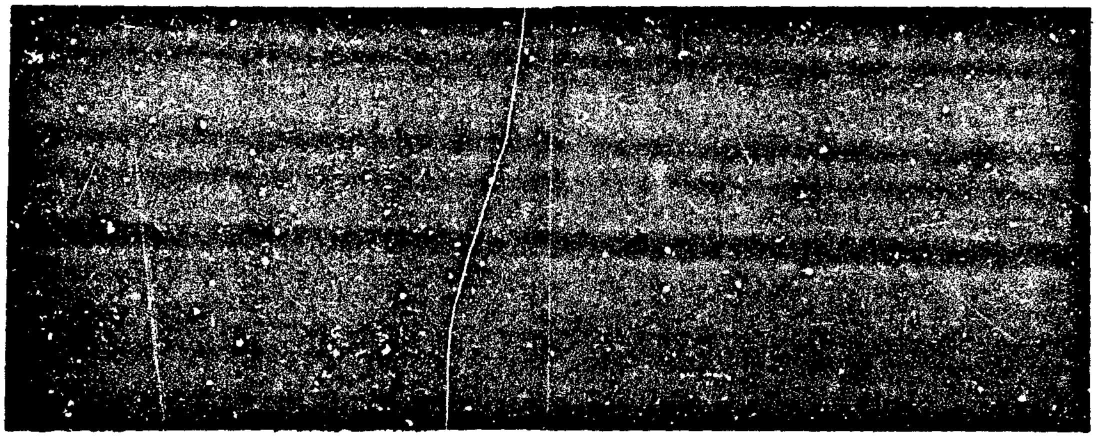
The photograph of the 10mm cloud at 5 seconds shows horizontal dipoles on the outside of the cloud and most of the high angle ones concentrated in the central active region with just a few at the bottom of the cloud in the same way as was seen with 28mm dipoles

CLOUD GROWTH IN THE WIND TUNNEL

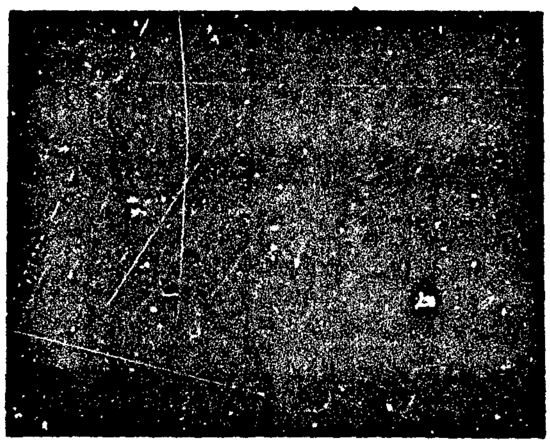
dipole length 10 mm



2·0 secs. 5·0 secs.



10 secs. 20 secs.



40 secs.

Figure 3

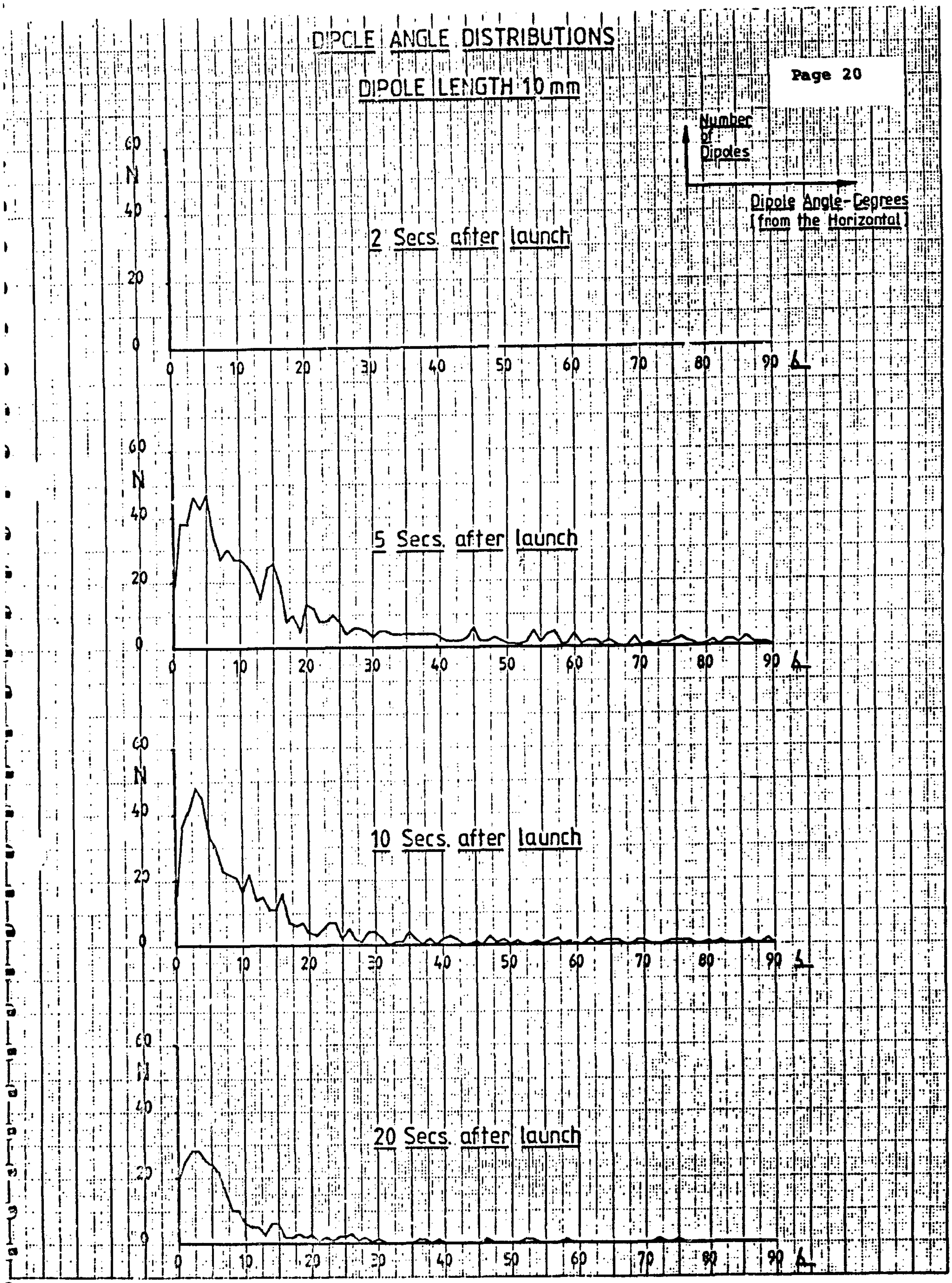

DIPOLE ANGLE DISTRIBUTIONS
DIPOLE LENGTH 10 mm
Number of Dipoles
Dipole Angle-Degrees (from the Horizontal)
2 Secs. after launch
5 Secs. after launch
10 Secs. after launch
20 Secs. after launch
N
0
20
40
60
0
10
20
30
40
50
60
70
80
90

Figure 4

The 10mm cloud appears to be separating into two smaller ones in the 5 second still with a gap between them just to the left of the centre of the field of view. This feature can be traced through the rest of the photographs. Such characteristics are common but completely random and are not restricted to 10mm clouds.

Increasing development of the cloud is shown in the next photograph, taken at 10mm seconds, which also contains some evidence of vertical columns where dipoles are stacked one above another in vertical lines. This is similar to what was seen in the 28mm cloud at this time.

The number of dipoles in the photograph had been severely depleted by 20 seconds and the rate of loss was so high that the cloud did not last much longer than 40 seconds.

It is readily apparent in all the photographs, even the 5 second one, that the horizontal or near horizontal dipoles far outnumbered the high angle ones which indicates a rapid dipole stabilisation process operates with 10mm dipoles.

The series of angle distribution graphs for 10mm dipoles is given in Figure 4. They support the conclusions drawn from the 28mm distribution graphs in that there is some movement of the peak in the distribution towards the lower angles on the left of the graph, but they do not show the trend as clearly as in the 28mm graphs. They do not show any significant increase in the amplitude of the graph in the 1 to 3 degree region, probably because the 10mm stabilisation process was quicker and the measurement times did not happen to coincide with the increase.

The number of dipoles at 10 seconds had reduced by nearly 30 per cent of the count at 5 seconds which indicated a more rapid growth of the 10mm cloud. This would also reduce any peak in the 1 to 3 degree region.

The impression gained from the film was that the 10mm cloud had a very low rate of growth initially, but beyond some critical point, around 3 seconds, the growth suddenly became rapid. If this was indeed the case there was nothing obvious in the film to explain why it should be so.

Dipole Angle Distribution For 50mm Dipoles.

There are several difficulties in dispensing 50mm long aluminised glass dipoles for experiments such as those described in this report. The major problem is birdnesting, which is caused by the severe distortion usually present in dipoles of this length. The birdnests form a large area of turbulence in the air above them which affects any free flying dipoles in the rest of the cloud. The physical size of the birdnests and the turbulence caused is roughly proportional to dipole length so that of the four dipole lengths used the 50mm dipoles produce not just the most but also the physically largest birdnests whose effects cannot be ignored in this sort of measurement.

Physical contact between dipoles can also contribute to birdnesting and so to avoid this problem only a small number of dipoles were dispensed for this series of measurements. Even so the close proximity of the dipoles at 2 seconds meant that detailed angle measurements were not possible before 5 seconds.

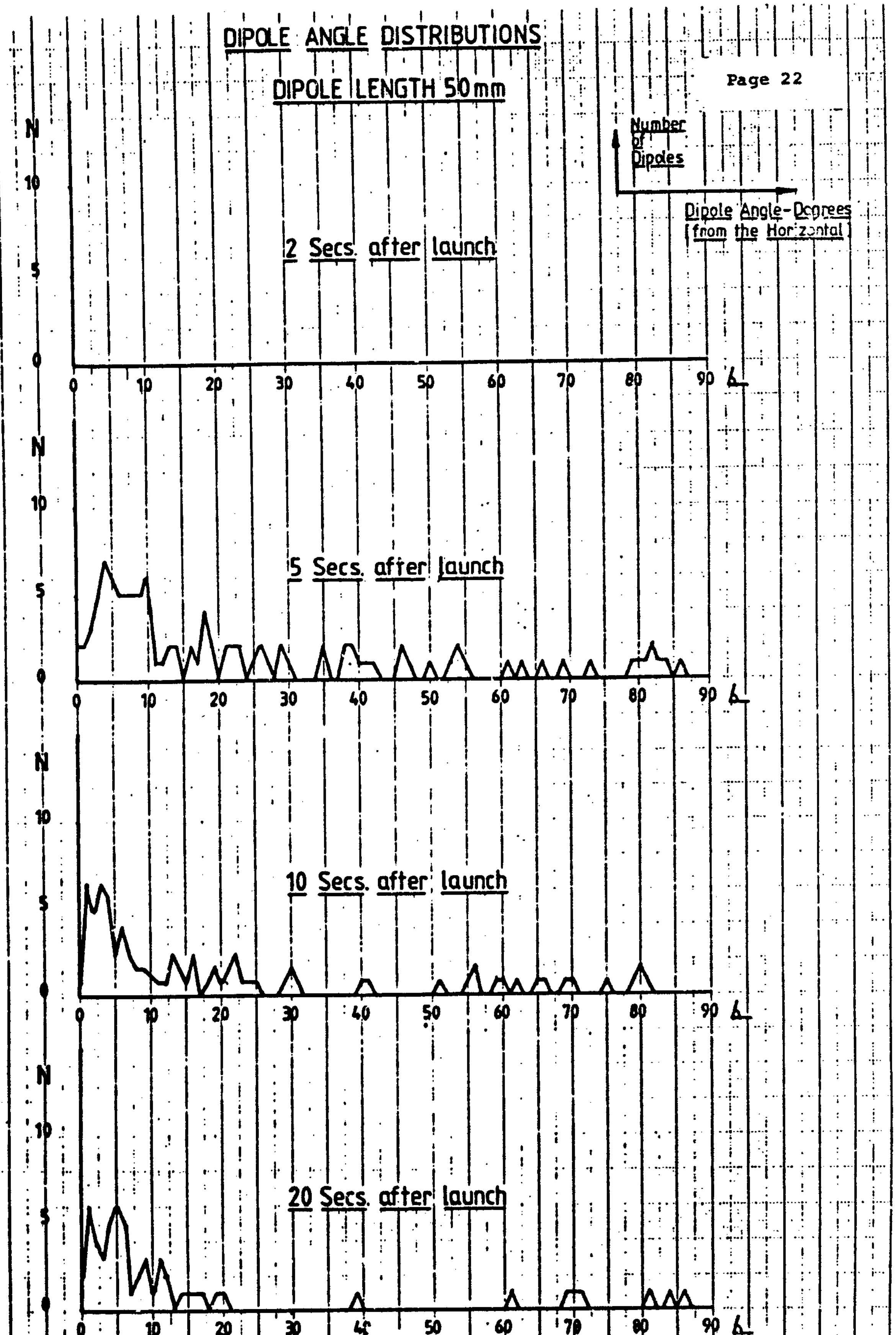

DIPOLE ANGLE DISTRIBUTIONS
DIPOLE LENGTH 50mm
Number of Dipoles
Dipole Angle-Degrees (from the Horizontal)
2 Secs. after launch
5 Secs. after launch
10 Secs. after launch
20 Secs. after launch
N
10
5
0
0 10 20 30 40 50 60 70 80 90

Figure 5

The angle distributions for the 50mm dipoles show similarities with those already discussed, irrespective of the difficulties. Briefly, the distribution extends up to 90 degrees but with a major peak or mode in the 5 to 10 degree region. At 10 seconds the mode has moved left to the 2 to 5 degree region with a reduction in the number of dipoles at high angles. At 20 seconds the decline in dipole number, familiar from the 10 and 28mm graphs, has taken over, as shown in Figure 5.

Now that the vertical drop method of dispensing used here has proved viable, it should be possible in the future to increase the number of dipoles by dropping them from several dispensers rather than from just one. Indeed, the dispenser could now be developed from a point source device to become a distributed area dispenser, launching a greater number of dipoles over a larger area than two or three square centimetres used of these measurements - perhaps even using more than one distributed area dispenser.

Dipole Angle Distribution For 15mm Dipoles

The pattern of angle distribution for the 15mm dipoles is shown in Figure 6 and is similar to those for the other three dipole lengths, tending strongly towards the horizontal flight motion and showing the number of dipoles declining with time.

There is some evidence of a rise in the number of dipoles at 2 to 5 degrees in the 5 second graph when compared with the 2 second one and of a drop in the number of dipoles at high angles. This tends to underline the rapid shift of the distribution towards the lower angles, as has been seen for the other dipole lengths.

The number of dipoles dispensed in the 15mm experiment was considerably greater than in any of the other experiments. This appears to have influenced the cloud growth in a way not apparent in the angle distribution graphs, but illustrated when the number of dipoles is plotted against time, as discussed later under Cloud Growth Rates.

In broad terms, therefore, the 15mm results are largely compatible with those for the other dipole lengths. However, there was an important point of difference related to the method of launching the dipoles as discussed next.

Effect Of The Dipole Launching Method.

The 10, 28 and 50mm angle distribution measurements were made by launching the dipoles in a vertical orientation into the wind tunnel. This was achieved by using a single dipole dispenser which had been developed by this investigator prior to the contract. This dispenser, which is completely mechanised requiring no operator skill, dispenses dipoles from a reservoir and launches them into the air. The dispenser does not damage or distort the dipoles in any way and it has a dispensing rate which can be varied from below one dipole a second up to several thousand per second, although the rate is dipole length dependant. The vertical orientation was achieved by fitting a curved dipole orientating ramp to the dispenser so that the dipoles slid down the ramp and were vertically orientated as they commenced their flight.

It was important to establish whether the number of dipoles dispensed and the dispensing method influenced the pattern of the angle distribution. A comparison was made, therefore, between the results obtained from the

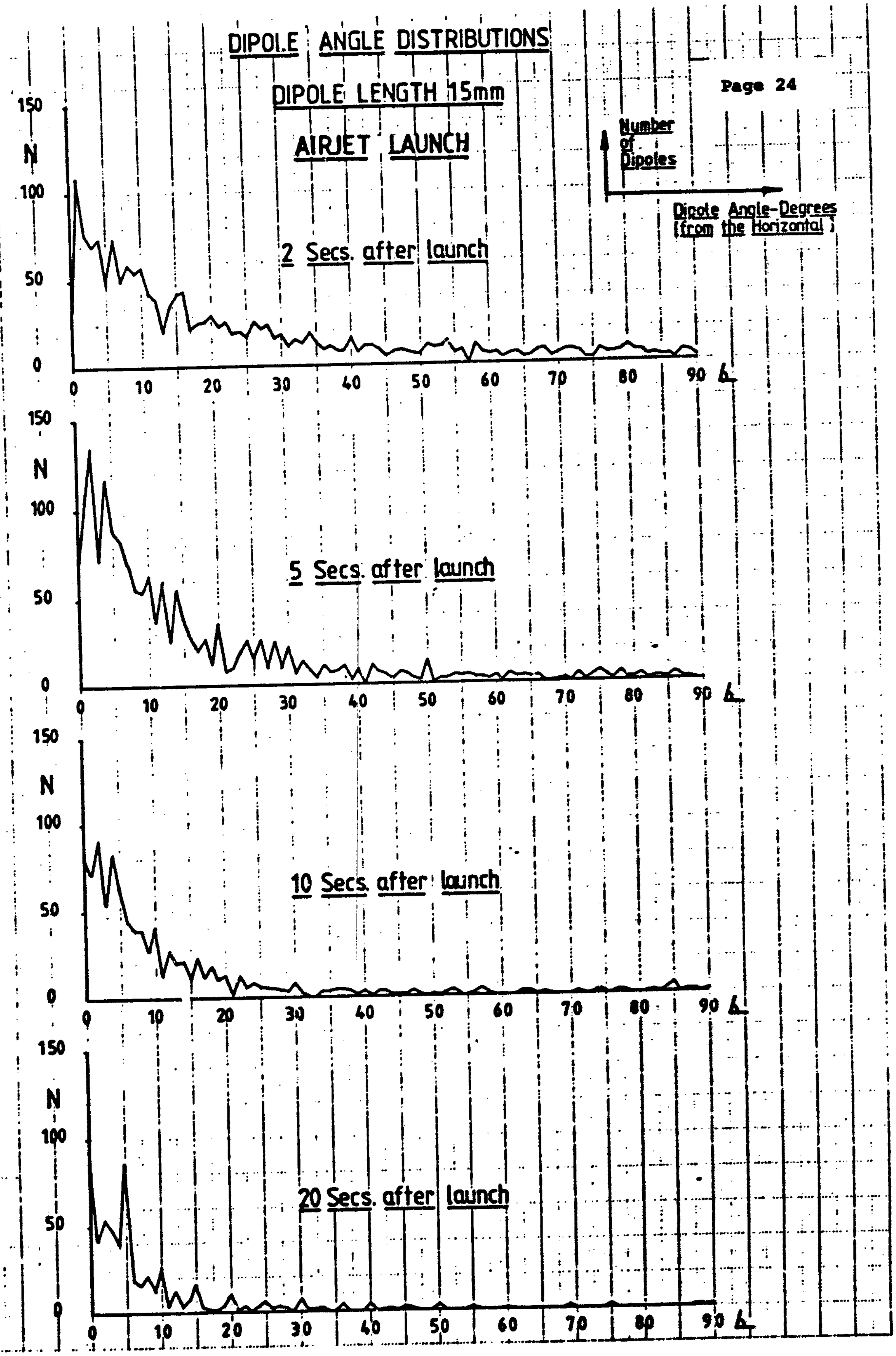
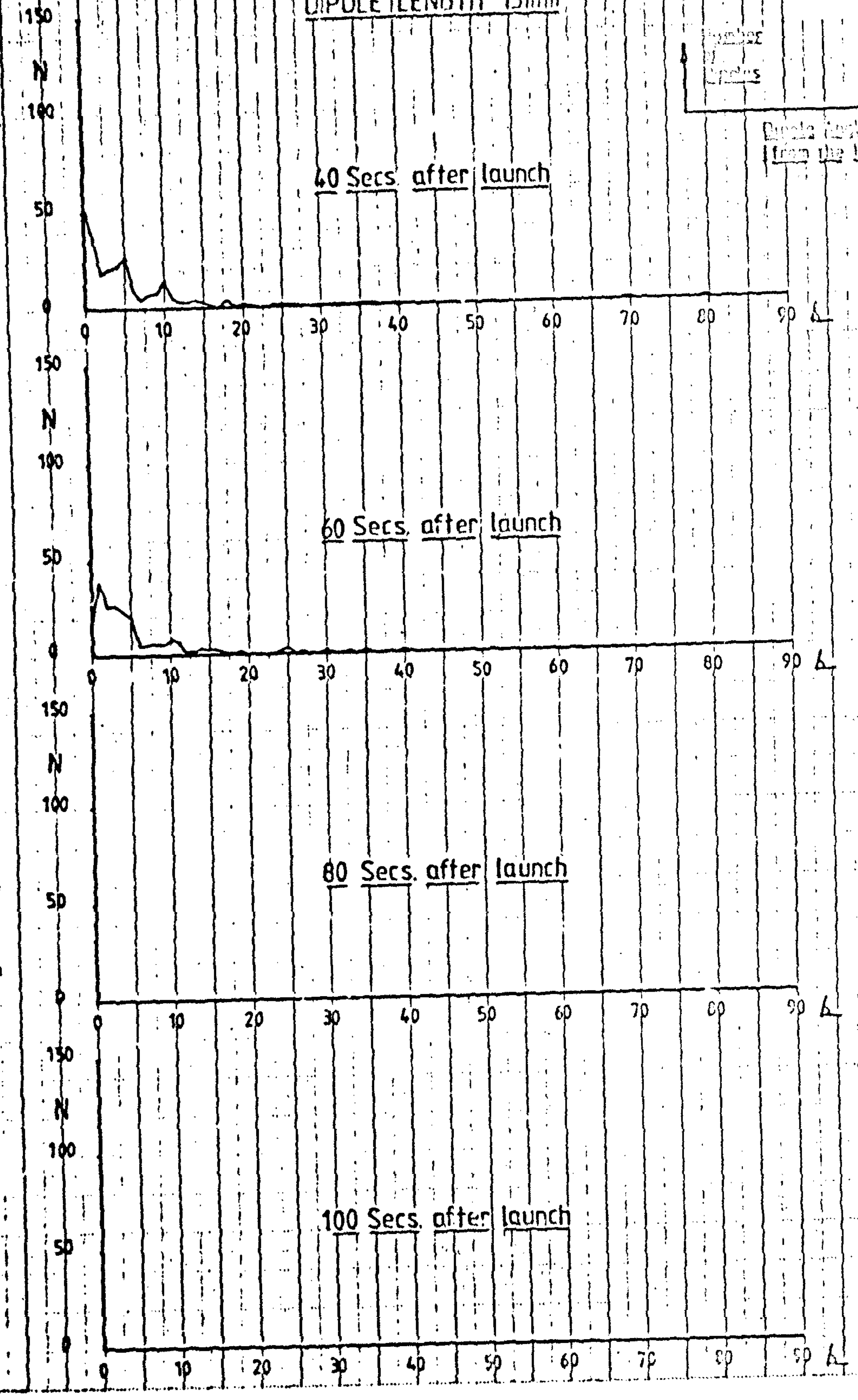

DIPOLE ANGLE DISTRIBUTIONS
DIPOLE LENGTH 15mm
AIRJET LAUNCH
Number of Dipoles
Dipole Angle-Degrees (from the Horizontal)
N
2 Secs. after launch
5 Secs. after launch
10 Secs. after launch
20 Secs. after launch
0
50
100
150
0
10
20
30
40
50
60
70
80
90

Figure 6

DIPOLE ANGLE DISTRIBUTIONS

DIPOLE LENGTH 15mm



vertically launched 10, 28 and 50mm dipoles and those for the 15mm dipoles which were launched by an airjet method.

The airjet operates at a very low velocity from an orifice of less than 1mm diameter. It strips the dipoles sequentially from an opened pack of chaff and projects the separated dipoles into the airstream in the wind tunnel. The opened pack is cradled in one hand while the airjet is being manipulated with the other hand. The air velocity in the jet is kept as low as possible, just sufficient to launch the dipoles without damaging them, and achieving this balance requires considerable skill. This method has been used over several years of wind tunnel work and it is thought to give a pseudo-random initial dipole angle. Its strengths are that it spreads out the dipoles very well, enabling large quantities to be launched rapidly, and it is repeatable. But it also has several limitations. Chief of these is that the method is manual, its mechanisation having not yet been successfully achieved for laboratory measurements. In addition, while birdnesting is low with this method it cannot be avoided altogether, especially if the dipoles are longer than 15mm.

Comparison of the angle distribution results for the airjet launched 15mm dipoles with the other dipoles suggests that the method of dispensing does have some influence on the angle distribution, affecting the time taken for the dipoles to become horizontal. This can be seen when the 2 second graphs are compared for the 15 and 28mm dipoles. By this time the airjet launched 15mm dipoles have a greater proportion of dipoles biased towards the horizontal than do the vertically launched ones. This is not altogether surprising, especially in view of the zero velocity stabilisation experiments discussed later, since the airjet injected dipoles are launched into an orientation closer to the horizontal and so are part stabilised at launch.

Comparison Of The Four Dipole Lengths.

The angle distribution of the graphs recorded the number of dipoles at any given angle between the horizontal and the vertical. An alternative way of considering the results is to identify the percentage of dipoles which measure 45 degrees or less and which therefore lie nearer to a horizontal than a vertical orientation. This approach has been adopted in Figure 7 which presents three bar charts which identify the percentage of dipoles with angles between 0-45 degrees, 0-30 degrees, and 0-15 degrees. Each bar chart compares the four dipole lengths at several time intervals between 2 and 100 seconds to see whether the relationship changes with time and with dipole length.

Three main points are emphasised by Figure 7. Firstly, it clearly demonstrates that all four dipole lengths had flight angles which were predominantly close to the horizontal. Taking first the broadest category which contained dipoles with angles measuring 45 degrees or less, it can be seen that while the readings range from 66 per cent to 100 per cent, all but two of the readings lie between 80 per cent and 100 per cent. Only the 28mm dipole lengths at 2 and 5 seconds gave readings of less than 80 per cent. In other words, the overwhelming majority of dipoles have angles measuring 45 degrees or less.

When an angle of 30 degrees is taken as the cut-off point, only five readings fall below the 80 per cent mark, and the lowest of these is 52 per cent for the 28mm dipoles at 2 seconds. Even when 15 degrees is taken as the limit, all but five readings are above a level of 66 per cent.

Secondly, the flight angle of all four dipole lengths became closer to the horizontal as the time after dipole launch increased. The table below provides a general summary of the percentage of the total number of dipoles visible in a frame which had flight angles within the three categories of 15, 30 and 45 degrees and of how this percentage changed with time. The figures in the table are approximate means for the four dipole lengths to show how close the dipoles were to the original:

Time after launch	Dipoles between 0° - 15°	Dipoles between 0° - 30°	Dipoles between 0° - 30°
5 seconds	50%	70%	80%
60 seconds	80%	90%	100%

Thirdly, the shorter dipole lengths were always closer to the horizontal than were the longer dipole lengths. The fact that the 15mm dipoles were closer to the horizontal than the 10mm ones is an anomaly caused by the airjet dispensing method used for the 15mm dipoles which launched dipoles closer to the horizontal than did the other dispensing method.

The Processes Occurring During Dipole Stabilisation.

An explanation of the processes whereby dipoles change their flight angles towards the horizontal needs a preliminary description of what appears to be one of the basic characteristics of cloud growth. This explanation is based on several years of study into all types of commercially available chaff dipoles. Although the processes were identified before this research contract this work has refined and quantified them.

It can be readily shown that when a dipole falls through the air it forms a turbulent sheet of air above it, and in the wind tunnel it is easy to show that two dipoles can aerodynamically interact if one gets into the turbulent sheet from a physically lower dipole. The flight angle of the upper dipole is then increased and that angle changes rapidly with time. This interaction may be transient and it happens when the change in the upper dipole's flight angle produces a new flight motion causing the upper dipole to move away from the lower dipole's turbulence after which the upper dipole will stabilise back into its original flight motion. Dipoles have never been observed to change their flight motion permanently by natural means. However, sometimes the interaction can be almost permanent, but more often it lasts for periods of several minutes [20 minutes has been observed] when the new flight of the upper dipole brings it physically below what was the lower dipole, usually by means of a short dive. The new upper dipole then suffers the effects of the turbulent sheet of the new lower dipole. When this happens the dipoles appear to dance as a couplet and the process is quite common, as indicated already, persisting for minutes at a time for some kinds of dipoles.

COMPARISON OF THE FOUR DIPOLE LENGTHS

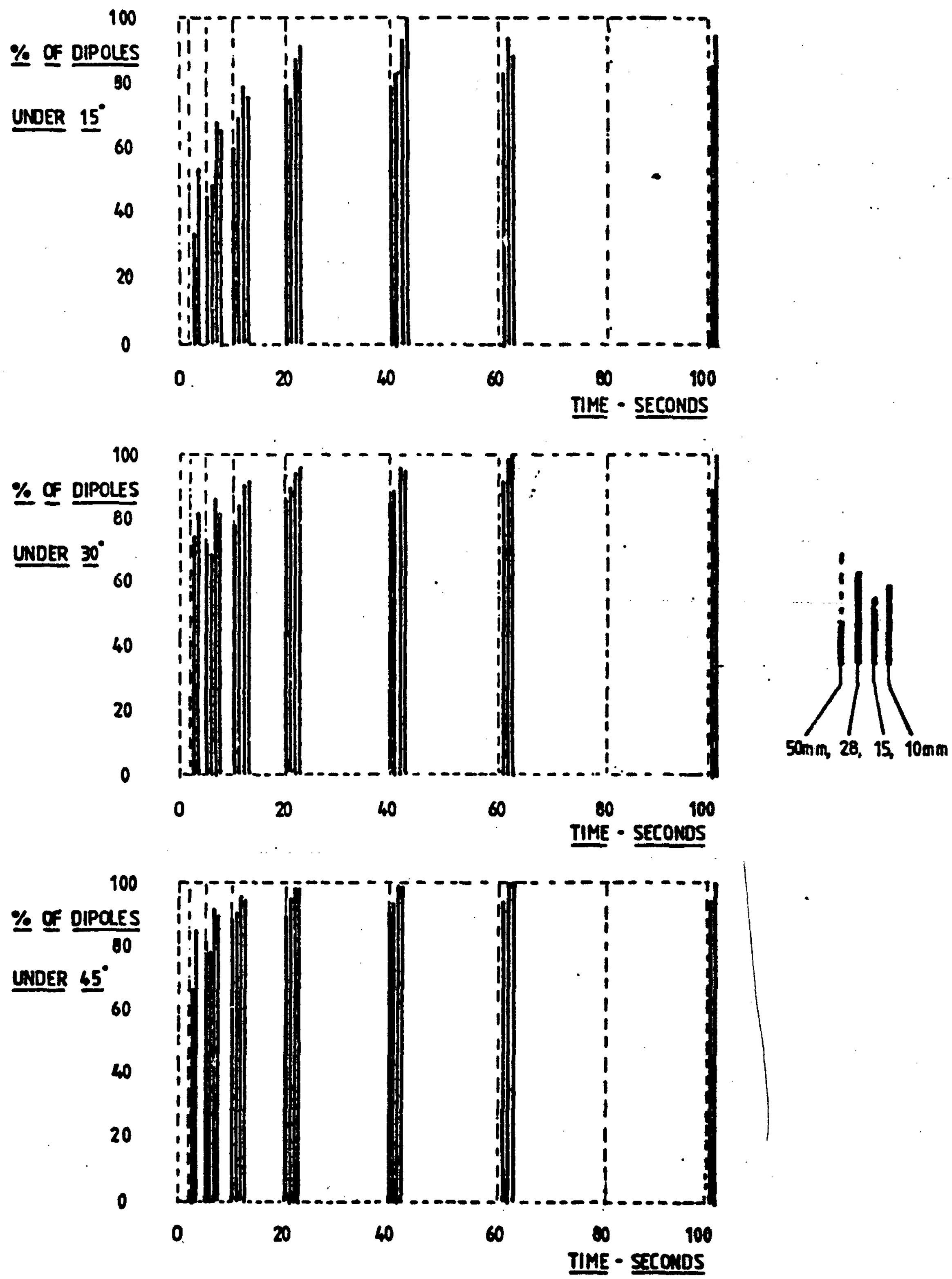


Figure 7

The upper dipole at any moment also has its own turbulent sheet which adds to the turbulence from that of the lower dipole. If more dipoles are added above the two interacting dipoles then the new dipoles will be influenced by the turbulence and the total turbulence will be increased above the new group and so on. The dipole motions within the group have not been studied in detail except in one spectacular case which showed where dipoles recirculate around the cloud. In that situation the effect is known to depend on the dipole length, the dipole cross sectional dimensions, [which is equivalent to dipole distortion] the number of dipoles in the cloud and the rate at which they were injected into the interacting region.

Those dipoles in a cloud which are initially independent of an interacting region can be dragged into the turbulence and then into the interacting region itself and so the region can grow in volume. But this happens only in very high density clouds or, to be more precise, when dipoles are very close together, that is, the cloud does not need to be physically large.

Dipoles, particularly at the centre of the interacting region, can appear to be trapped in the region to some extent. This seemed to be the case for the first two seconds of the life of the 10mm cloud analysed for this contract. There is also a process which assists dipoles to escape and which appears to operate at the edges of the interaction region. It seems to be dependent on the characteristics of the dipole flight motion once dipoles escape from the interacting region.

Neither the central trap nor the outer assistance regions have been studied and are not understood, but it is clear from the filming for this contract that virtually all of the high angle dipoles were in the interaction region. As they escaped they went into their basic horizontal flight motions, so the low angle peaks on the angle distributions increased in amplitude before the dipoles moved out of the field of view of the camera and all of this happened in about 5 seconds. It is a field of study which could well be investigated further since major characteristics such as cloud growth rate (ie RCS growth rate), polarisation ratio and Doppler characteristics and effiency are influenced by it, to name just a few.

Zero Air Velocity Experiments.

It was clear throughout the analysis from which the dipole angle distributions were obtained that the dipoles were rotating from the initially vertical orientation in which they were dropped into the wind tunnel to the horizontal orientation of their normal flight in under five seconds and sometimes in under two seconds. It was surprising that this stabilisation was so fast and an additional series of experiments was made to investigate what was happening in more detail.

The method was to measure the distance through which the dipoles fell before they stabilised into their normal flight mode. The measurements were made by dropping vertical dipoles into still air, filming the flight from the drop and analysing the film to obtain the measurement. Still air conditions extended the stabilisation distance to its true magnitude and, incidentally, removed any question of effects of a vertical airstream. The experiments were made in the wind tunnel with the motor/fan combination switched off, that is, with zero air velocity in the tunnel. The tunnel was used because the dispenser, lights and black background were already installed there, and, in addition, the tunnel sides provided a draught free environment.

The vertical dipole dispenser was set at a very low dispensing rate to prevent interaction, turbulence and chimney effect, and so to illustrate better the short distance required for individual dipoles to stabilise. There was no reason to time these experiments and so no time digits appear in the photographic stills.

Six individual stills from the films of the four dipole lengths are given in Figure 8. The stills of the 10mm dipoles and particularly those of the 28mm ones show the dipole stabilisation path very clearly. The 28mm photograph shows the elementary curve of the stabilisation path traced out by successive dipoles on both sides of the dropping line. The stabilisation distance obviously varies in that vertical dipoles can be seen below others which are just stabilising. In the 15mm photograph in particular the vertical dipoles must have dropped before the stabilising ones because the vertical dipoles have travelled a greater distance. The second 10mm still does in fact show two stabilisation distances

The 50mm photographic stills are interesting because they show a dipole distortion which is common in longer dipoles. This curvature, which can be traced back to the manufacturing process, produces a particular flight motion which is illustrated in the second 50mm still. Having been dropped vertically, the dipoles transiently stabilise with the convex curvature downwards, but this is followed by a reorientation into a vertical flight motion which is succeeded by another transient stabilisation with the convex curvature upwards. This in turn is followed by another vertical flight and the oscillation continues, usually indefinitely. Dipoles can be seen in all of these orientations in the lower photograph, those with the convex up being the three which are apparently touching just above and to the right of the 50mm digits. This oscillation between transient stabilisations is known as 'vertical epicycloidal' motion and is common in dipoles with this curvature, but it is accompanied by excessive birdnesting in normal chaff usage.

In all photographic stills of the four dipole lengths, horizontal dipoles can be seen above and to the right of the dispenser. These are dipoles which settled on a background panel which was 300mm behind the black background tunnel wall. They were from a previous measurement, taken when the motor was running and are not therefore, connected with the zero velocity measurements. They can be seen in the same positions in all the stills and should be ignored.

Although the stabilisation distance was variable, as was seen in the photographs, guide figures are:-

Dipole length	Stabilisation distance
10mm	80mm
15mm	160mm
28mm	200mm
50mm	400mm

This indicates that the stabilisation distance in still air is very small and that the relationship with dipole length is roughly linear for dipoles which are suffiently far apart not to interact.

Another sequence of timed stills taken from a film made under the same conditions as for the four dipole lengths above is presented in Figure 9. The only difference is that the rate of dispensing was increased to illustrate

DIPOLE ORIENTATION
[air velocity = zero]

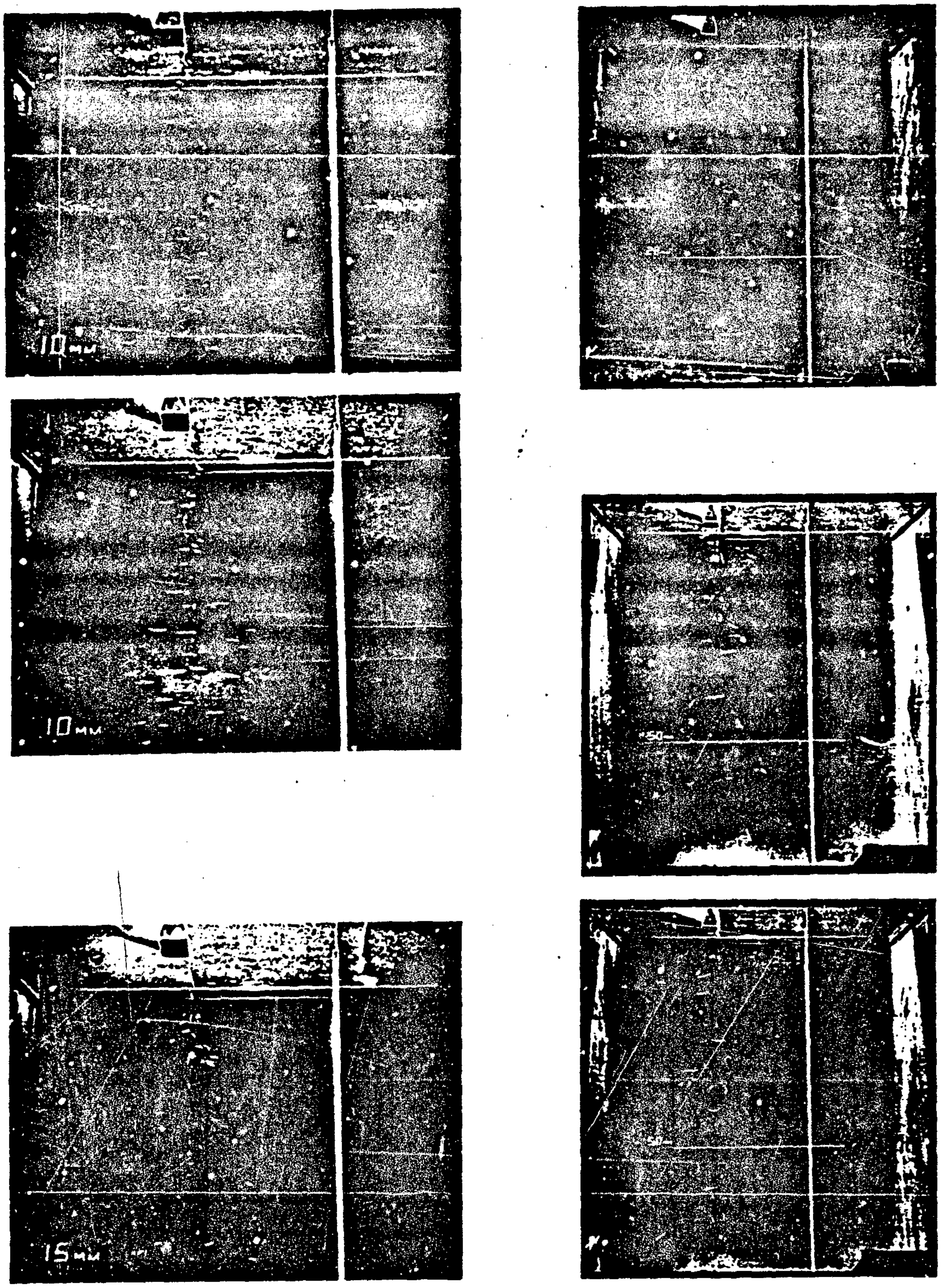


Figure 8

that the interaction effects are not caused by the air velocity in the wind tunnel. The sequence also provides a link between the angle distribution measurements and the dipole stabilisation ones.

The 28mm dipoles were dropped in a vertical orientation with the tunnel motor switched off. Dipole launch started at zero seconds on the timer and was then continuous. It was not a short burst as was used in the angle distribution measurements. At 0.2 seconds some of the dipoles were already at 60 degrees to the horizontal, and at 0.3 seconds one dipole had already reached the horizontal. An air turbulence formed as the number of launched dipoles increased, as shown in the 0.7 second still. The effect was to extend the stabilisation distance from the typical 200mm to about 400mm. The same central turbulence volume is apparent in the 1.4 second still, perhaps more clearly, and the dipoles which escaped from it are projected, either side, in horizontal orientation. At 2.3 seconds the pattern was being overwhelmed by so many dipoles being dispensed that they caused a downward draught through the rest of the cloud. This downward draught also sucked down the subsequently dispensed dipoles, preventing them from stabilising until they eventually came out of the bottom of the draught. For convenience, this process is called the 'chimney effect'.

The Growth Rate Of Chaff Clouds.

Each film frame which was analysed, as described under the angle distributions, also gave a figure for the total number of dipoles which was in the field of view at that time. Since the timer was included in each frame, the decay in the number of dipoles over the period of each experiment can be plotted. This has been done in Figure 10 to illustrate how the dipole count changed with time.

The curves for all four dipole lengths have been plotted on the same two axes. They show the relatively large number of 15mm dipoles which were launched by the airjet technique and demonstrate how the number launched by the vertical drop dispenser was dependent on the dipole length.

The general form of the four curves indicates an exponential decay process. If this decay is of the form:-

$$N = N_0 \, e^{-Bt} \qquad (1)$$

where N = the number of dipoles visible at time t
N_0 = the equivalent number of dipoles at $t=0$
B = a constant (the cloud growth constant)

N_0 is not necessarily the actual number of dipoles launched, as will be shown later, consequently it has been referred to as the equivalent number of dipoles at $t=0$.

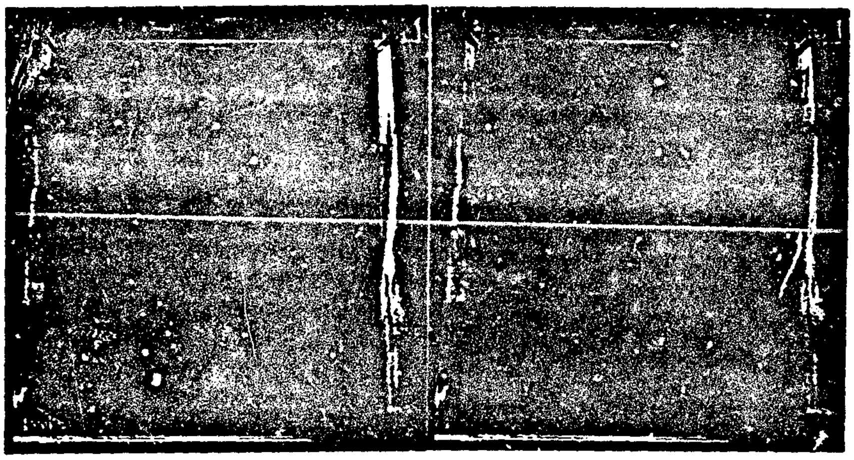
Then taking natural logarithms of (1) :-

$$\mathrm{Ln}N = \mathrm{Ln}\, N_0 - Bt \qquad (2)$$

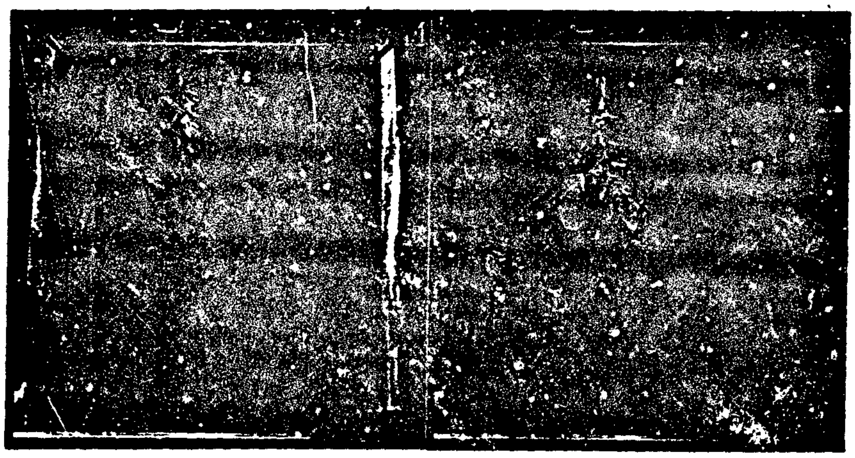
If (1) is true then plotting LnN against time will give a straight line of slope B.

The logarithm plots are shown in Figure 11. It is reasonable to draw straight

AERODYNAMIC INTERACTION IN STILL AIR



0·2 secs. 0·3 secs.



0·7 secs. 1·4 secs.

2·3 secs.

Figure 9

lines through the plotted point for all the dipole lengths after five seconds and this tends to support the view that the decay has the form of equation (1). However, the number of pints on each graph is small.

The first 15 seconds of the 15mm plot is intriguing because the points in that region are significantly above any reasonable straight line. The dipole number at t=0 was almost certainly 1675, that is 7.42 on the LnN scale since the analysis, both of the 2 and the 5 second frames, gave virtually the same number of dipoles. The intercept on the LnN axis shows an equivalent number, of 854 dipoles. This implies that the processes occuring in the first 15 seconds were somewhat different from those operating from 15 seconds onwards.

The interaction within the 15mm cloud was more intense than in the clouds of the three other dipole lengths because of the high dipole count, as borne out by the films, but also possibly because the dipoles were relatively close to the horizontal during the period that they were so close together. In view of the fast growth process which was operating, as shown by the points being above rather than below the straight line, and the interaction characteristics seen on the stills for vertically dropped dipoles, the first ten seconds of cloud life could usefully be investigated in more detail.

If equation (1) is differentiated the constant B may be interpreted as the fraction of the instantaneous number of dipoles which leave the field of view per second. So the initial reaction is to assume that the 10mm cloud was growing faster than the three other clouds. However, the slope of the LnN plot must be strongly dependent on the specific air velocity in the wind tunnel, and it is most likely that the air velocity for the 10mm cloud was slightly different from the 0.3 metres per second used for the three other measurements.

Comparing the approach of equation (1) and (2) with elementary radioactive decay theory, it is feasible to go on to consider a half life for the clouds and to arrive at figures of about 25 seconds. But at this stage it is not reasonable to try to quantify the growth in that way, because of the strong dependence on wind tunnel air velocity. It would be necessary to run a series of dipole number decay measurements at various air velocities in the wind tunnel and establish the minimum slope attainable before it would be reasonable to quantify the growth further. This would be necessary since both higher and lower velocities will give a higher slope than that for the true slope.

The decay in the number of dipoles flying in the wind tunnel is caused by the increasing inter-dipole distance and the consequent growth in volume of the cloud, so the decay data can be related to the growth of the cloud. This could be linked with the practical problem of eventually arriving at a theory of radar cross section growth rate. A possible path by which this might be achieved is outlined next.

A more detailed study that the measurements here could arrive at the number of dipoles in the elemental volume which is the camera's field of view and define how that number changed with time, dipole quantity and dipole length, as already sketched out in Figure 10.

The cloud from the elemental volume will grow into adjacent elemental volumes surrounding the field of view and, at any time, the total number of dipole in the surrounding volume will be known.

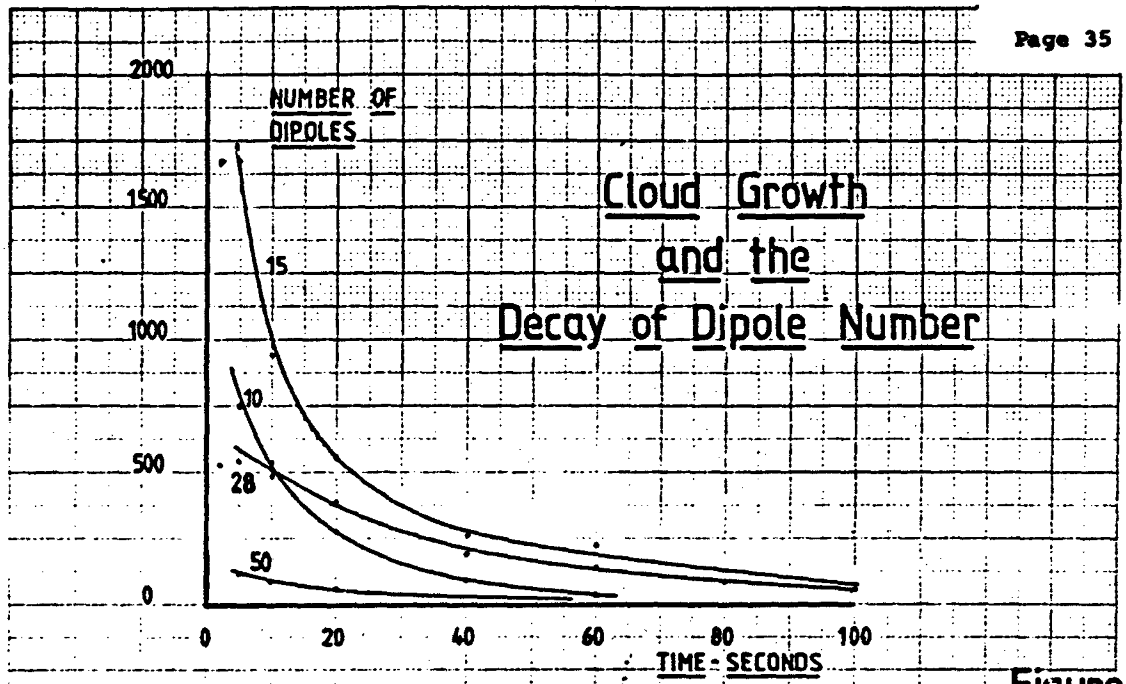


Figure 10

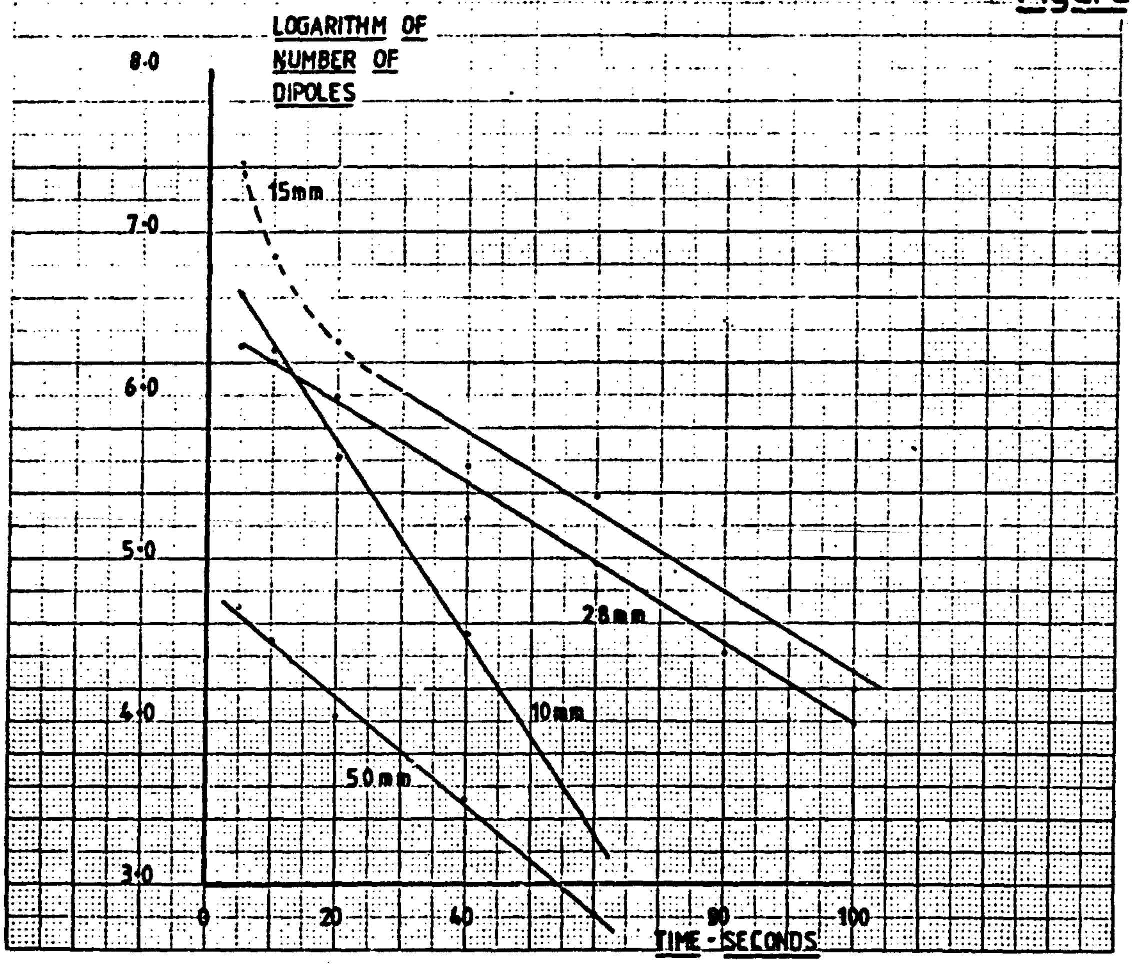


Figure 11

If the decay rate in the surrounding volumes can be assumed to follow the same law as in the field of view, ie the central volume, then the total cloud volume can be calculated at any time, possibly including allowances for interaction effects and dipole density variations (which are known to be prevalent at higher densities than those used here).

If the total cloud volume of a known number of dipoles can be calculated at any time then the cloud growth rate is known.

If the practical relationship between the dipole density and the actual radar cross section of the elemental volume were known it would be possible to predict the actual radar cross section of a full cloud containing a known number of dipoles. The radar cross section versus dipole density relationship could be measured by putting the wind tunnel into an anechoic chamber. The effects of high altitude, turbulence and birdnesting could also be simulated to bring the measurements closer to the operational conditions.

CONCLUSIONS.

The objectives of measuring the distribution of flight angles and its time dependency for four dipole lengths have been achieved and the work has significantly exceeded the requirements of the contract in several respects.

A powerful method, using an advanced vertical wind tunnel which has been specially modified to overcome the limitations of other tunnels, has been developed further in this work, enabling the growth of dipoles to be recorded and studied for periods up to about two minutes. Several sequences of photographic stills taken from the original film have been included in the report along with detailed graphs of the results.

The angle distribution has been shown to be similar for all four dipole lengths studied with only minor differences between them.

These distributions had dipoles at all angles between the horizontal and the vertical, but only within the first five seconds of the cloud's life, and even then only if the dipoles had been launched in a vertical orientation. The distribution in the first few seconds had a pronounced peak at about five degrees to the horizontal.

The dipoles quickly stabilised after the first few seconds into their normal flight motions which were predominantly at angles close to the horizontal with the shorter dipole lengths flying closer to the horizontal than the longer ones at any given time. The most prevalent flight motions of aluminised glass dipoles is within five degrees of the horizontal.

Many more dipoles would be dispensed in an operational application than were launched in this series of experiments and so the time scales for stabilisation will differ. But the process of stabilisation does take place under similar sea level conditions and this has been witnessed in dual polarisation radar measurements.

A comparison was made between two methods of launching dipoles in the angle distribution experiments. These were an airjet injection and a unique method of launching dipoles in a vertical orientation. The results from the airjet were shown to be different from but strongly related to the vertical launch distribution.

Most dipoles with large flight angles were contained in a central region of the cloud where dipoles were aerodynamically interacting with each other. The processes occuring in the interaction region have been described in some detail but were very complex and more study is needed to understand them.

A series of experiments in still air showed that the distance through which a vertical dipole would fall before stabilising into its near horizontal flight motion was very short and usually much less than one metre. The distance was dependent on dipole length and could be extended by several orders of magnitude if quantities of dipoles were dispensed rather than single ones.

A study of the decay in the number of dipoles in the wind tunnel as time increased indicated that an exponential law was being followed after the first ten seconds. A path has been sketched out by which the growth rate of the radar cross section of chaff clouds might be predicted with the aid of further study.

RECOMMENDATIONS.

The work reported here has taken the form of baseline measurements performed under sea level conditions and in the absense of the operational complications of turbulence and other influences. It has identified several areas of further study, and these are outlined below.

The angle distribution of the dipoles could be measured under high altitude conditions typical of air force applications by installing the wind tunnel and camera in a high altitude chamber and repeating the measurments reported here.

Progressive levels of air turbulence could be introduced in the wind tunnel, initially under sea level conditions, to determine the influence on the angle distribution. Prior work indicates that the effect would be substantial.

The film shot for this report is of a detailed scientific nature rather than a general informative one. So this report even with its photographic stills cannot convey the dynamic character of chaff clouds. It is recommended that an educational film is produced to illustrate the features of chaff clouds and serve as a vehicle for a discussion of chaff use, development and research.

The processes operating within the interaction region of a chaff cloud could be examined in more detail to discover the exact nature of the separation of dipoles which constitute the growth of the cloud. This would reveal whether there is a growth trap as experienced here in the first few seconds of the 10mm cloud, and whether there is a dipole projection mechanism at the edges of the interaction region, both of which could influence the growth of radar cross section.

The correlation of a dipole's fall rate with its flight angle and, more specifically, the horizontal and vertical velocity components of the flight angle should be measured for various dipole lengths. This could be achieved by linking a video tape recorder to a television camera and recording a single dipole dispenser launching single dipoles into still air and measuring the parameters under freeze frame conditions. Incidentally, this would produce a second check on the angle distribution measurements and also enable the number of dipoles with high angle flight motions to be measured more accurately.

A specific study should be made of dipole cloud growth rates, as outlined in this report, with examination of the effect of dipole density and, independently, of dipole length.

In view of the characteristics of interaction, the effects of an increased quantity of dipoles on the distribution could be investigated further. This would mean increasing the area over which the dipoles are dispensed to increase the quantity of dipoles and to minimise birdnesting. Computerised analysis would also be needed.

Consideration should be given to changing the fundamental flight motion of aluminised glass dipoles from the horizontal to a higher angle orientation to obtain a more rapid growth rate. Methods of achieving this can be put forward.

The mechanism, or mechanisms, by which birdnests are formed could be investigated since birdnests can represent a vast loss of dipoles, particularly for long dipoles.

The radar cross section of wind tunnel clouds and the microwave quantification of shielding could be attempted.